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Evaluating Effects of Character Appearance on Ownership and Learning in Virtual Applications

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EVALUATING EFFECTS OF CHARACTER APPEARANCE ON OWNERSHIP AND LEARNING IN VIRTUAL APPLICATIONS

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Human Centered Computing

by
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Abstract

Virtual applications are now a dominant commercial and social platform. Sixty-seven percent of households own a gaming device [4], and eighty-one percent of the United States population has a social media profile [81]. Now, virtual reality appears to be the next technological frontier that will take over mainstream markets. New, low-cost devices for virtual reality or mixed reality such as the Oculus Rift, Sony's PlayStation VR, or Samsung's Gear VR are already available or have been announced and might even outperform previous high-cost systems [94]. With the prevalence of this technology, it is important to know how it influences us. One common factor that has remained popular in virtual applications throughout its evolution are characters. How does the appearance of characters affect us in virtual applications and virtual reality? Towards understanding these effects, this research presents findings on results when character model appearance is altered in an educational application and in self-representative avatars. Results from our experiments show that allowing character customization in an educational software results in higher learning outcomes for participants. We also find that when controlling self-avatars, some participants can feel that they own any virtual hand model given to them in virtual reality. In addition, we find that participants generally feel the strongest ownership for virtual hands that appear human-like. Finally, we find that participants experience stronger feelings of ownership and realism when they are able to control virtual hands directly rather than with a hand-held device, and that the virtual reality task must first be considered to determine which modality and hand size are the most applicable. These results contribute to knowledge for how to best create characters for users in virtual applications and environments.

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Publications from This Research

Note: Results in Study 1, Study 2, and Study 3 have been published in the following papers:

- Lorraine Lin and Sophie Jörg. Need a hand?: How appearance affects the virtual hand illusion. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '16, pages 69–76, 2016
- Lorraine Lin, Dhaval Parmar, Sabarish V. Babu, Alison E. Leonard, Shaundra B. Daily, and Sophie Jörg. How character customization affects learning in computational thinking. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '17, pages 1:1–1:8, 2017
- Lorraine Lin, Aline Normoyle, Alexandra Adkins, Yu Sun, Andrew Robb, Yuting Ye, Massimiliano Di Luca, and Sophie Jörg. The effect of hand size and interaction modality on the virtual hand illusion. In *2019 IEEE Virtual Reality Conference*, 2019

Further Publications

- Gurjot Singh, J. Edward Swan, II, J. Adam Jones, Lorraine Lin, and Stephen R. Ellis. Depth judgment measures and occluders in near-field augmented reality. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*, APGV '09, pages 127–127, New York, NY, USA, 2009. ACM
- Lorraine Lin and Sophie Jörg. Do cartoons feel pain?: Using the virtual hand illusion to test human response to degrees of realism. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, SAP '15, pages 134–134, New York, NY, USA, 2015. ACM
- Lorraine Lin and Sophie Jörg. The effect of realism on the virtual hand illusion. In *2016 IEEE Virtual Reality (VR)*, pages 217–218, March 2016
- Danielle C. Herro, Lorraine Lin, and Michelle Fowler. Meet the (media) producers: artists, composers, and gamemakers. *Journal of Applied Research in Higher Education*, 9(1):40–53, 2017
- Dhaval Parmar, Sabarish V. Babu, Lorraine Lin, Sophie Jörg, Nikeetha D'Souza, Alison. E. Leonard, and Shaundra B. Daily. Can embodied interaction and virtual peer customization in a virtual programming environment enhance computational thinking? In *2016 Research on Equity and Sustained Participation in Engineering, Computing, and Technology (RESPECT)*, pages 1–2, Aug 2016
- Valentin Schwind, Lorraine Lin, Massimiliano Di Luca, Sophie Jörg, and James Hillis. Touch with foreign hands: The effect of virtual hand appearance on visual-haptic integration. In *Proceedings of the 15th ACM Symposium on Applied Perception*, SAP '18, pages 9:1–9:8, 2018

Chapter 1

Introduction and Motivation

From storybook fables to preschool shows, characters are some of the first teachers, perhaps even figures, that people interact with. The importance of characters as more than an entertainment platform is gaining traction as characters are becoming recognized for their appeal as instructors or assistants in educational, medical, and military applications [31,34,37]. In virtual applications and virtual reality, characters are fictional and non-sentient visual representations of beings, created from digital models and code, that are stored with the rest of a game or application's data. However, they have been shown to generate realistic reactions. For example, in a reprise of Milgram's famous experiments on authority and obedience [60], Slater et al. [79] found that participants who saw and heard a character being shocked tended to respond to the scene as if it were real. "This ability of virtual characters to elicit realistic responses from humans has been used in further experiments, and interestingly, this effect holds true even for scenes with abstract human figures with little degree of realism [66]." Thus, it is important to know how to tailor characters to respective applications so they are as effective as possible without being distracting or overwhelming. We observe the effect of character model appearance in three studies:

1. *Effect of character model choice options on learning.* The ability to select or customize characters in educational applications and games has been shown to influence factors related to learning effects such as transfer, self-efficacy, and motivation. Most previous conclusions on the perception of virtual characters and the effect of character assignment in interactive applications have been reached through short, one-task experiments. To investigate long-term effects of assigning versus customizing characters as well as explore perceptions of personal character appearance, we conducted a study in which sixth

and seventh grade students were introduced to programming concepts in seven one-hour sessions over two weeks. With a between-subjects design, in which some of the students could alter their character while others were not given that possibility, we examined the influence of the presence or absence of character choice options on learning. We hypothesized that students have higher learning outcomes when they can choose and customize how their character looks compared to when they are assigned a character. We confirm this hypothesis for a category of learning (Remember and Understand) and give insights on students' relationships with their character.

2. *Effect of character model on the virtual hand illusion.* How does the appearance of a virtual hand affect own-body perception? Previous studies have compared either two or three hand models at a time, with their appearances limited to realistic hands and abstract or simple objects. To investigate the effects of different realisms, render styles, and sensitivities to pain on the virtual hand illusion (VHI), we conducted two studies in which participants took on controllable virtual hand models with six distinct appearances. We collected questionnaire data and comments regarding responses to impacts and threats to assess differences in the strength of the VHI. Our findings indicate that an illusion can be created for any model for some participants, but that the effect is perceived weakest for a non-anthropomorphic block model and strongest for a realistic human hand model in direct comparison. We furthermore find that the responses to our experiments highly vary between participants.
3. *Effect of character model size and interaction modality on the virtual hand illusion.* Most commercial virtual reality applications with self avatars provide users with a "one-size fits all" avatar. While the body may be scaled to the user's height, other body proportions, such as limb length and hand size, are rarely customized to fit an individual user. Prior research has shown that mismatches between users' avatars and their actual bodies can affect size perception and feelings of body ownership. In this paper, we consider how concepts related to the virtual hand illusion, user experience, and task efficiency are influenced by variations between the size of a user's actual hand and their avatar's hand. We also consider how using tracked gestures or a tracked controller affects these concepts. We conducted a 2x3 within-subjects study (n=20), with two levels of input modality: using tracked finger motion vs. a hand-held controller (Glove vs. Controller), and three levels of hand scaling (Small, Fit, and Large). Participants completed 2 block-assembly trials for each condition (for a total of 12 trials). Time, mistakes, and a user experience survey were recorded for each trial.

Participants experienced stronger feelings of ownership and realism in the Glove condition. Efficiency

was higher in the Controller condition and supported by play data of more time spent, blocks grabbed, and blocks dropped in the Glove condition. We did not find enough evidence for a change in agency and the intensity of the virtual hand illusion depending on hand size. Over half of the participants indicated preferring the Glove condition over the Controller condition, mentioning fun and efficiency as factors in their choices. Preferences on hand scaling were mixed but often attributed to efficiency. Participants liked the appearance of their virtual hand more while using the Fit instead of Large hands. Several interaction effects were observed between input modality and hand scaling, for example, for smaller hands, tracked hands evoked stronger feelings of ownership compared to using a controller. Our results show that the virtual hand illusion is stronger when participants are able to control a hand directly rather than with a hand-held device, and that the virtual reality task must first be considered to determine which modality and hand size are the most applicable.

The results from our research contribute to knowledge on how to best create characters for virtual applications such as digital games, educational software, training simulations, or rehabilitation applications. This knowledge is important for optimizing learning applications, increasing user learning and motivation, and creating virtual environments in which we feel comfortable and in which we can effectively interact to learn, work, communicate, and have fun.

Chapter 2

Related Work

In this chapter, we summarize previous work regarding character model appearance and control. As the body of literature on these subjects is large, we focus on research that directly influenced ours. Section 2.1 is a general summary on previous effects of model appearance on character motion, perception, and behavior. Section 2.2 is the pool of research the first study (Chapter 3) builds upon; it summarizes effects of model appearance and customization on learning. Section 2.3 is the previous literature the second study (Chapter 4) builds upon; it summarizes effects of model appearance on the rubber hand and virtual hand illusions. Section 2.4 is the past work our third study builds upon; it summarizes the effects of model size on the rubber hand and virtual hand illusions. Finally, as we are interested in how differing controls influence perception of a self-avatar, Section 2.5 summarizes the effects of interaction modality.

2.1 Effect of Model Appearance on Character Motion, Perception, and Behavior

Virtual characters vary from being highly cartoony in appearance to very realistic. Previous research has shown that appearance changes how some motions are perceived [14, 27, 57]. In many cases, the more realistic characters appear, the more prone they are to being expected to move naturally. A similar effect has been shown when only changing the render style and not the shape of a character, with motion anomalies being considered more unpleasant on realistic human than cartoon render styles [55]. However, realism does not necessarily affect motion interpretation: character appearance does not influence the perception of a character's

emotions [58] or persuasiveness [96]. In summary, participants likely have different reactions to different render styles or shapes of virtual characters, especially if they move. The appearance of a virtual character influences the way we perceive and judge it [55, 56, 88]. It also influences us when we interact with a virtual character or see ourselves as one [35, 43, 71, 73, 74, 93].

Interactive media can influence user behavior by allowing a dimension of experience above viewing: by being able to control one character specifically or take on a social role in a game world, interactivity allows an override of the distance between player and character. Hefner et al. [25] propose that people mainly experience interactive media through a monadic (identification-driven) connection with characters. Identification with a character can further be split into two categories: players can create a character that is simply a replica of their actual self, or players can create a character that embodies an ideal image they would like to have of themselves. Jin [30] found that players reported greater immersion during game-play if they were primed with hope and played the game using an avatar reflecting the actual self, or if they were primed with duty and then played the game using an avatar reflecting the ideal self.

2.2 Effect of Model Appearance and Customization on Learning

Being able to interact or identify as a character provides positive effects in general to media experiences. Allowing users to select or customize characters has been found to result in further beneficial effects. In a World of Warcraft study by Lim and Reeves [39], just having the option to select an avatar produces higher arousal, measured by skin conductance activity and heart rate, during gameplay. Turkey and Kinzer [86] observed participants in a customization group (CG) versus a non-customization group (NCG) playing Lord of the Rings Online. They found that both avatar-based customization and time positively impacted players' identification and empathy with their avatars. Participants also rated hairstyle as the most important customization aspect, followed by hair color and eye color. Qualitative findings showed that many of the CG players customized characters to have some aspect of themselves, such as a skill (playing an instrument) or physical characteristic (hair, eyes, build.) The researchers suggest that, for educational games, avatar-based customization may increase students' motivation, and that if customization is available, players will identify with characters further and focus more on events related to their characters.

The addition of a character to a learning system does not necessarily have a direct impact on learning [7]. However, the ability to control character appearance via customization or selection, in contrast to simply having a character assigned, impacts factors associated with learning effects in users. Baylor conducted

two studies to observe these factors. In the first study [10], students were given the ability to select pedagogical agents that would give a presentation on coping with college life. African-American students rated their agent as “more facilitating of learning, more credible, more human like, and more engaging,” than Caucasian students rated their agents. African-American students were also significantly more likely than Caucasian students to choose agents based on ethnicity. Females were more likely to select cartoon-like agents than males, and females were significantly more likely than males to use personal experience for choosing their agents, while males were more likely to choose agents based on previous teachers. Research has shown that character appearance has effects even if characters are just assigned. In the second study [8], students were assigned agents to aid in learning basic instructional planning skills. Assigned male agents were overall more motivational than assigned female agents: working with male agents resulted in higher reported self-regulation and greater self-efficacy, and male agents were rated as more useful. Such a positive bias towards male agents, although the effects were small, was not found in the first study.

2.3 Effect of Model Appearance on the Rubber Hand and Virtual Hand Illusions

First demonstrated by Botvinick and Cohen [13], the rubber hand illusion (RHI) is a body ownership illusion (BOI) where participants report that a rubber hand feels like it is part of their own body. Synchronous touching and visual feedback of the candidate effector and the participant’s hand induce a feeling of ownership for the fake hand [17, 32, 85]. In many RHI studies regarding realism, different skin colors and hand shapes of believable rubber human hands do not affect the strength of the RHI: as long as the effector appears to belong to a human, the illusion will occur [19, 48]. However, exceptions to these findings do exist in certain conditions: Hohwy and Paton showed that the RHI can occur for objects that do not resemble hands, but only if the illusion has been created beforehand by a fake hand that is then instantaneously replaced by the object [28]. Guterstam et al. found that empty spaces can be taken on by healthy participants as part of their own bodies [21].

Elaborating on texture, the RHI is stronger when the texture of the fake hand resembles human skin instead of a glove [22]. Realistic textures also increase the strength of full-body BOIs, allowing the illusion to occur even with asynchronous visuotactile cues [54]. However, realism may be detrimental in certain situations. Won et al. found that participants in virtual reality given a third arm with a biological appearance instead of a

mechanical appearance had worse performance on tasks [92]. An interaction of biological appearance with the arm detached from the participants' body showed participants in this condition performed the most poorly, likely due to an "Uncanny Valley" effect of the arm appearing unnatural, and thus, distracting [62].

Individual differences can play into the strength of the rubber hand illusion [43,53]. For example, sensory suggestibility is a personality trait defined by how one reacts to suggested sensory information that is physiologically implausible. Marotta et al. found that participants who were classified as having high sensory suggestibility experience the rubber hand illusion more strongly than participants classified as having low sensory suggestibility [53].

The RHI is known as the VHI when it occurs in virtual environments, with the rubber hand replaced by a virtual one that is sometimes controllable with tracking devices such as data gloves or computer mice [49,50,75,80,95,97]. Perez-Marcos et al. found that participants felt that they owned a virtual hand more if it was connected to their body with a virtual arm, and that the effect carries over if the virtual hand's position was misaligned with their real hand. Ownership was assessed via subjective ratings [70]. Tieri et al. observed participants' feelings of ownership and electrodermal activity (EDA) regarding a virtual hand connected normally to the self-avatar's arm, connected with a wire in place of the wrist to the arm, disconnected due to a missing wrist, or disconnected with a glass panel between the hand and arm. Although participants subjectively rated only the normally connected hand as evoking high levels of ownership, the EDA showed high amplitudes for both the normally connected hand and the wire-connected hand when a virtual knife hit the hand [84].

VHI studies have either compared two or three effector appearance conditions at a time, and the influence of the effector appearance is an important question still. Yuan and Steed conducted the first of these studies; they found that the VHI exists for a realistic hand, but not for an arrow cursor [95]. Further studies have mixed or contradicting results regarding the initial finding that the VHI only exists when the hand appears roughly like the participant's own hand in shape and animation (see Table 2.1). Participants feel more ownership for a virtual human hand than a virtual rectangle, but significant ownership illusions are still present for the nonhuman effector [51]. Significant ownership illusions are present for a human hand and cat claw, but participants feel more ownership for the human hand and thus also more anxiety for the human effector when threatened [97]. Argelaguet et al. [2] also found that ownership was strongest for a virtual human hand, but observed that agency (a sense of control over a body part or object) is stronger for less realistic virtual hands due to less of a mismatch between virtual hand animations and the participant's actions. BOIs have even been shown to work for highly abstract or nonexistent effectors. Ma and Hommel [50] found that participants can take on balloons as part of their bodies, and the VHI is comparable for two-dimensional squares and realistic

Table 2.1: Controllable virtual hand representations in previous VHI studies

Study	Models	Significant Results
Yuan and Steed 2010	realistic hand, arrow cursor	Strong illusion for hand, weak to no illusion for cursor
Ma and Hommel 2015a	realistic hand, balloon, square	Strong ownership for realistic hand, balloon, and square; ownership increased for effectors that look connected to participants' bodies
Ma and Hommel 2015b	realistic hand, rectangle	Stronger ownership for hand over rectangle
Zhang and Hommel 2015	realistic hand, cat claw	Stronger ownership for hand over cat claw
Argelaguet et al. 2016	realistic hand, iconic hand, abstract hand	Strongest ownership for realistic hand, stronger agency for iconic and abstract hand

hands.

The previous literature raises a question: Why are BOIs more easily invoked for a wide range of models in the VHI, but not in the RHI?

The exact process underlying BOIs is a dominating theoretical issue in the field. Experimental conclusions point to two general approaches for driving BOIs: they are either sufficiently induced by only bottom-up processes, or they occur as an interaction of top-down and bottom-up processes [51]. In support of the latter approach, since our own-body perception relies not only on continuously updated sensory-motor information (bottom-up processes), but also on higher-order cognitive (top-down) processes [36], it should be logical that shapes differing from the human body should always receive less acceptance for being taken on as part of one's own body.

Yet, the approach of top-down and bottom-up processes interacting to produce BOIs does not account for studies where abstract objects and empty spaces can be taken in as part of one's body. Ma and Hommel [51]'s observations on the VHI occurring for balloons and virtual squares implies that a body-like realistic appearance and anatomical plausibility of the candidate effector is unlikely to be absolutely necessary for the illusion to occur. They suggest that top-down factors become more important when there is not enough sensory information to rely on, so body-part resemblance would then compensate for controllability. Thus, if agency is removed as a factor, ownership and location (of the hand) would account for the illusion, and the unmoving physical rubber hand in the RHI is more critically judged because people are substituting top-down processes in place of the ability to move the hand.

2.4 Effect of Model Size on the Rubber Hand and Virtual Hand Illusions

Model appearance has been shown to influence the virtual hand illusion. While the virtual hand illusion can even be created with abstract shapes, human-like hands induce stronger feelings of ownership than non-anthropomorphic hands or abstract objects [51] [97] [2] [43]. For example, Schwind et al. found that participants felt like they owned human hands more than robot hands, robot hands more than cartoon hands, and cartoon hands more than abstract hands [77]. People also experience a high level of ownership when the hand model is controlled based on their motions. For example, they experience a higher level of ownership for a hand with six fingers when the extra finger is animated based on the tracking of the ring and pinky finger. [76]. Time spent inducing the rubber hand illusion increases its effect as well. Participants viewed a reflection of their left hand that was normal-sized, magnified, and minified while performing synchronized finger movements. They felt more strongly about ownership, agency, and location of the hand reflection for all reflection sizes after the finger movement task, as well as for the normal-sized reflection [89]. Stronger feelings of ownership does not always correlate to stronger feelings of agency, or the ability to control virtual body parts: Argelaguet et al. observed different hand realisms with direct control and found that the virtual human hand generated the strongest level of ownership, but the less realistic hands generated higher levels of agency [2]. If similarity to our own hands and control through our hands increase the virtual hand illusion, one could assume that a similarity in size and direct control are important factors.

The body-based scaling hypothesis proposes that the estimate of the size of virtual objects depends on the size of the virtual hands: the body is the metric for defining object size, so participants given a large hand underestimate object sizes, and participants given a small hand overestimate object sizes [46] [64]. In Haggard and Jundi's observation of the rubber hand illusion, after watching the stimulation of a large or small glove in synchrony with their own hand, participants were asked to hold cylinders and guess their weights. The large glove evoked a size-weight illusion in which the held cylinders were perceived to be smaller objects that weigh more [23]. Ogawa et al. observed how realism and hand size affect the perceived size of a held cube. They found that the cube appeared smaller for high, medium, and low avatar realism when the hand size was enlarged, but the cube's size was perceived smallest for the high realism avatar compared to the medium and low realism avatar [65]. Linkenauger et al. also found that objects are perceived to be smaller when a hand is magnified. However, hand sizes do not affect objects that are too big to be grasped, and thus are beyond the mechanism of judgement [47]. Pavani and Zampini found a constraint that the rubber hand illusion occurs

when the fake hand is larger or similar in size to, but not smaller than participants' hands [69]. Additionally, the scale of surrounding objects or the environment can exert an effect on the perception of body size. People perceive virtual hands as larger and objects as smaller in virtual reality; but when interacting with objects, they tend to perceive the overall size of both depending on if they see the object or their hands first [63].

Context also affects perception of body size. Given a controllable child body instead of an adult body scaled down to the size of a child, participants overestimate object sizes more than in the small adult body and have faster reaction times on an implicit association test for child-like attributes [5].

2.5 Effects of Interaction Modality

Controllers and gestures have both been used as input devices for VR applications. Gesture-based interactions may create a more natural experience but are also frequently associated with diminished performance. McMahan et al. found that users reported that motion-based input as more fun in a racing video game, but that traditional controllers were easier to use. Motion-based input controls were also associated with diminished performance [59]. Moehring and Froehlich compared finger-based and controller-based ray casting in a CAVE and HMD. They found that users preferred finger-based interactions even though controllers had better performance. They also showed that adding visual and tactile feedback could improve the performance of the finger-based interactions [61]. Lin and Schulze compared grasping gestures for direct manipulation, magnetic grasping for remote manipulation, and interacting with objects via buttons in VR. Participants in a pilot study provided feedback that they felt the grasping was more natural, but that the button was more reliable [40]. Porter et al. explored users' behavior in a VR game that implements both direct, motion-based controls and indirect, button-based controls. They found that while users enjoyed motion-based controls more, both motion controls and buttons were frequently used side-by-side. This was attributed to a number of factors, including the physical cost of motion based controls, differences in the capabilities of the motion controls compared to the buttons, and uncertainty about the reliability of the motion controls [72].

Perceived naturalness, enjoyment, and efficiency can also be affected by the design of the interaction mechanics, especially when considering realistic interaction mechanics vs. more "magical" techniques. However, unlike the clear tradeoff between enjoyment and performance with gesture-based input vs. controller-based input, it is possible for less strictly realistic interaction mechanics to improve performance while also creating a more favorable user experience. For example, Eriksson evaluated the Go-Go technique (where a user's hand stretches out longer than their real arm) and a ray-casting technique for selection and manipulation.

Both techniques performed at similar levels of efficiency, but Go-Go was rated as more satisfying, intuitive, and immersive, despite that it is less “natural” than ray-casting [18].

Chapter 3

Study 1: Application to Learning

The previous chapter gives us an outline of existing research in the fields of character appearance and interaction modality. In this chapter, we describe the initial study we conducted to further knowledge on the existing work of effects of model appearance and customization on learning.

3.1 Introduction and Motivation

Previous research indicates that character appearance affects learning [6]. One advantage of virtual applications compared to real life is that the appearance of virtual agents or teachers can easily be altered to personal preferences. Studies on games have shown that allowing avatar options has positive impacts on players [39, 86]. We therefore believe that providing character customization choices in an educational application might have a positive effect on student learning.

Most previous studies on the effect of character appearance or customization in interactive applications are relatively short interventions displaying agents with a rather static role [8, 10, 30]. To investigate the effects of character customization options on learning effects, we use the learning software VEnvI (Virtual Environment Interactions). VEnvI is a system and curriculum aimed at middle school students that combines computer science and dance concepts. It uses an embodied approach to teach students computational thinking in a motivating context [15, 16, 68]. Teachers explain six basic programming concepts: sequences, loops, variables, conditionals, functions, and parallel programming; and perform dance activities with the students that illustrate the concepts.

In parallel, students are introduced to the VEnvI software, which has a drag-and-drop interface with



Figure 3.1: Screen capture of the VEnvI interface. The virtual character can be seen on the top left. Move sequences and computational constructs, represented by blocks, can be chosen in the bottom left area and assembled to a dance in the drag and drop area on the right side.

code blocks similar to Alice [33], Scratch [52], or Looking Glass [20] as illustrated in Figure 3.1. Students use the computer science concepts they learned to create their own dances for a virtual character. They are encouraged to leave their seats and dance with their characters at any time. VEnvI furthermore supports virtual reality. With a VR headset, users can observe their character and dance beside it. Parmar et al. [68] describe the software and curriculum in greater detail. The system can be obtained by contacting its researchers and developers [87].

3.2 Experiment Overview

In our experiment, sixth and seventh grade students from a local middle school spent seven one-hour sessions over the course of two weeks using VEnvI to programmatically choreograph dance performances for virtual characters, which were either randomly assigned to them or which they customized at the beginning of the experiment. The main questions we aim to answer are:

- What are the effects of character customization vs. assignment on learning?
- How do students perceive their character? What relationship do they have to it?

The goal of our experiment is to investigate the effect of character customization on student learning and explore how students perceive the virtual character they work with. Our hypothesis is that students will

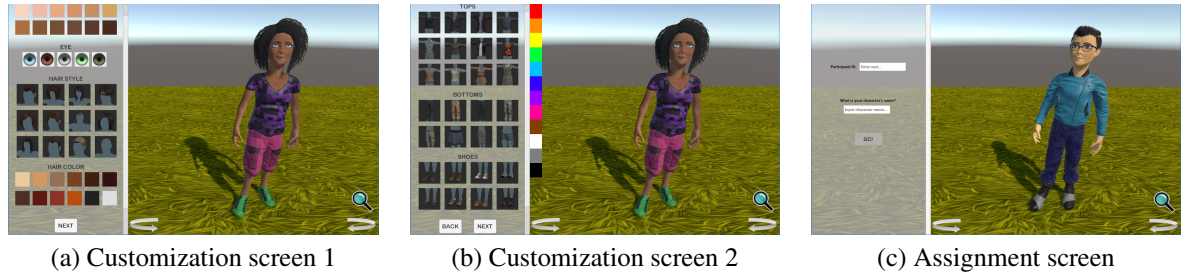


Figure 3.2: Customization and assignment screens.

have higher learning outcomes when they can choose and customize how their character looks compared to when they are assigned a character. To investigate this hypothesis, we used a between-subjects design: students were randomly assigned to a group where they had the option to customize their character (C) or to a group where they were assigned a character (A).

3.2.1 Customization and Assignment

The VEnvI software allows the user to customize their character using the Unity Multipurpose Avatar (UMA) system, an open-source avatar creation framework available in the Unity Asset Store [83]. With the UMA system in VEnvI, participants can choose character gender, as well as alter the character’s height, upper weight, lower weight, skin tone, clothing colors, and eye color. In a pilot test with the UMA system, participants commented on their characters mentioning that “it was creepy” and “it looked fake”. These comments suggest that the characters provided were not appealing to the demography, which could have invalidated our results.

For our experiment, we therefore created a new character customization system and integrated it into VEnvI. An androgynous child model along with its outfits, accessories, and base textures were provided by Adobe Fuse CC. These 3D assets were rigged and skinned in Maya 2016. Adobe Photoshop CC 2017 was used to further edit textures for tinting when necessary. A customization menu and edits to the existing VEnvI code allowing swappable character accessories, textures, and tinting were implemented within the Unity3D game engine. Our customization system provides 12 skin tones, 5 eye colors, 12 hair styles, and 12 hair colors on a first screen; 12 top styles, 8 bottom styles, 8 shoe styles on a second screen; and 7 glasses styles on a third screen (see Figure 3.2 (a) and (b)). The clothing and accessories could be tinted in 11 colors. Options for all customizable items were limited to twelve or fewer so participants would not spend too much time in the customization menu, but chosen to allow as much room for individuality as possible. Skin, hair, and eye color options offered were chosen to be inclusive to a wide demography. Hair, top, and bottom styles aimed to be as

balanced as possible, including a wide mix of female, male, and unisex styles. Characters for the assignment group (see Figure 3.2 (c)) were pre-designed to reflect a wide variety of demography and clothing styles using the same options. Figure 3.7 shows examples of characters created with our system.

3.2.2 Method

3.2.2.1 Participants

We conducted our experiment at a middle school in four groups: sixth and seventh grade students from a graphics communication class, and students in the same two grades from a dance aerobics class. There was no overlap in students between the two classes. The study was offered as an opt-in activity for the graphics communication class and was mandatory for all students of the dance aerobics class. Informed consent was obtained from all students whose data was used in this study and from their parents following the guidelines approved by our Institutional Review Board. Two dance aerobics class students did not consent and their data was discarded. Further five students' data were excluded as they missed some of the sessions. This led to a total of thirty-six participants (4M, 32F) in our analysis between eleven and thirteen years of age. The distribution of students in each group can be seen in Table 3.1. Of those, 26 identified as Caucasian, 3 as African American, 1 as Arab, 1 as Asian, 1 as Indian, 1 as Hispanic, and 3 as multiracial. For each group, the experiment consisted of seven one-hour sessions within a time span of two weeks.

Table 3.1: Participant distribution in our four groups

	graphics communication	dance aerobics
sixth grade	9 (3M, 6F)	12 (all F)
seventh grade	5 (1M, 4F)	10 (all F)

3.2.2.2 Design and Measures

Our experiment used a between-subjects design, with eighteen students in the customization condition (C) and eighteen students in the assignment condition (A). The independent variable is the type of character assignment provided, customization vs. assignment. The main dependent variable is the learning effect, measured with a cognitive pre- and post-test. Factors possibly related to learning effect, such as enjoyment and motivation, and to the appearance of the characters and the relationships students had with them, were also included. In total, our measurements are as follows:

Cognitive Pre- and Post-Test

The cognitive test can be found in Appendix C. This test was administered twice, once at the beginning and once at the end of our experiment. It tests for knowledge on computer programming concepts such as sequences, loops, if-else statements, variables, and functions. The questions from the cognitive test are inspired by Bloom's taxonomy [1, 12] and the SOLO [11] taxonomy. Both taxonomies are learning models that categorize educational objectives into different levels. Our cognitive test observes three of the six Bloom cognitive domain levels that build on each other: Remember and Understand, which is retrieving information from memory ("What is the purpose of a loop?"); Apply, which is taking known information and implementing it in a new situation ("Based on the blocks below, will the character perform the "Cha Cha" or "Clap?"); and Analyze, which is breaking down a complex problem into parts to better understand it ("What order should the block below be put into if I want the character to clap first, move to the right side, and then reverse twice?"). Our cognitive test also observes three of the five SOLO levels that build on each other: Unistructural, which is when students are able to answer one portion or aspect of a concept ("Look at the blocks below. When 'PLAY' is clicked, what will the character perform?"); Multistructural, which is when students grasp several aspects of a concept but treat them as independent components ("Give an example of a conditional in your life."); and Relational, which is when students are aware of the logic and steps they need to do to solve the problem ("Look at the blocks in Picture A and Picture B below. Would a character performing Picture A and another performing Picture B do the same thing?").

Experience Questions

Experience questions asked students about factors such as their confidence, interest in, and opinions on the importance of learning about dance and programming that might have changed due to experiencing VEnvI ("How likely are you to choose computing as a major in college?"). These questions were asked twice, once at the beginning and once at the end of our experiment. In addition, questions that were relevant once students had completed VEnvI, measuring enjoyment, ease of learning, and motivation, were asked at the end. The post-study experience questionnaire is displayed in Appendix D.

Character Questions

Students were asked questions regarding their character at the start of and after the study. Additional questions that were relevant once students had completed VEnvI were asked at the end ("How much did you

Table 3.2: Overview of experiment schedule

Session 1	Demographics, cognitive pre-test, experience questions, introduction to VEnvI, dance activity
Session 2	Sequences, dance activity, intro to VEnvI software and VR, character customization and questions
Session 3	Loops and parallelization combined with dance activities, implementation in VEnvI
Session 4	Variables, conditionals, and functions with dance activities, implementation in VEnvI
Session 5	Implementation of computing concepts in VEnvI
Session 6 and 7	Dance show, cognitive post-test, experience and character questions

feel like dancing with the character?”). The debriefing and character questionnaire is displayed in Appendix E. To examine if students tend to create characters similar to them, we took pictures of students together with their characters.

3.2.2.3 Procedure

The experiment took place over seven one-hour sessions spread over the course of two weeks following the VEnvI curriculum. An overview of the activities in each session is provided in Table 3.2. The detailed teaching plan can be found in Appendix A. In the first session, after filling out an initial demographic questionnaire, participants were asked to answer experience questions (see Appendix B) and complete the cognitive pre-test to the best of their abilities. Participants were invited to a discussion of what they think research is, and we summarized what to expect over the next two weeks. Finally, students learned some of the choreography available in VEnvI with an instructional dance activity.

In the second session, participants were introduced to the VEnvI software. Students were randomly assigned to one of our two conditions. In all remaining sessions, students were seated in two rows facing each other with a large space in-between where the dancing activities took place. Students in the customization condition were seated in one row and students in the assignment condition were seated in the other row. This procedure was chosen to ensure that the students from the different conditions could not look at each other’s screens and to avoid discussions amongst students that had customization options and students who did not have these choices. Students interacted with VEnvI on Apple Macbook Pro laptops.

Upon opening VEnvI, participants in the C group were given options to customize their character.

Once they were satisfied, they could name their character and proceed to the main VEnvI programming interface. This process took about five minutes. Participants in the A group had no control over their characters' appearance. Upon opening VEnvI, they viewed a pre-designed character randomly assigned to them, and the character creation process only consisted of naming their character before proceeding to the main VEnvI interface (see Figure 3.2 (c).) After allowing participants a few moments with their character and the VEnvI software, we asked the character questions. Participants were also introduced to the Virtual Reality setup: from this session on, they had access to view their dances in Virtual Reality through the use of an Oculus Rift head-mounted display and a Microsoft Kinect tracker (see Figure 3.3.)



Figure 3.3: The Virtual Reality setup.

In the next sessions, students were introduced to programming concepts intermingled with illustrative dance activities. For example, researchers explained the concept of loops, then invited participants to illustrate the concept by repeating a number of dance moves as if they were looped. In the last two sessions, students presented the dances they programmed and filled out questionnaires.

3.3 Results

We analyzed all questions we asked – the cognitive pre- and post-test, the experience questions, and the character questions – as well as the pictures of the students with their characters.

3.3.1 Cognitive Pre- and Post-Test

Participants' number of correct responses in the cognitive pre- and post-test were converted to a percentage score. The scores were normally distributed based on descriptive statistics analysis. We conducted

Table 3.3: Main effects of session in individual categories of the cognitive pre- and post-test. All effects showed increases in student scores.

Category	F-test, p-value, and eta-squared	Pre-test M and SD	Post-test M and SD
Remember and Understand	$F(1, 34) = 44.20$ $p < 0.001$ $\eta^2 = 0.565$	M = 8.33, SD = 14.64	M = 26.39, SD = 17.87
Apply	$F(1, 34) = 5.79$ $p < 0.05$ $\eta^2 = 0.146$	M = 29.63, SD = 16.37	M = 36.73, SD = 21.87
Analyze	$F(1, 34) = 6.39$ $p < 0.05$ $\eta^2 = 0.158$	M = 40.28, SD = 33.42	M = 54.17, SD = 30.18
Multistructural	$F(1, 34) = 54.21$ $p < 0.001$ $\eta^2 = 0.615$	M = 8.79, SD = 12.90	M = 26.85, SD = 17.49

a 2x2 mixed model repeated measures ANOVA with the cognitive pre- and post-test scores as a within-subjects repeated measures factor and the type of character choices provided – Customization (C) vs. Assignment (A) – as a between-subjects factor. We ensured Box’s M test of equality of covariance matrices was not significant. Mauchly’s test of sphericity was conducted to ensure error variance in groups of samples was found to be equivalent.

We found a main effect of session (pre vs. post) with $F(1, 34) = 28.178$, $p < 0.001$, $\eta^2 = 0.453$. Overall, on the cognition questionnaire, participants in the post-test session ($M = 36.90$, $SD = 16.33$) scored significantly higher than participants in the pre-test session ($M = 25.79$, $SD = 13.90$), $p < 0.001$, which shows that our VEnvI program overall was successful in teaching students concepts.

The results were separated into further categories for analysis: Remember and Understand, Apply, and Analyze questions according to Bloom’s taxonomy; and Unistructural, Multistructural, and Relational questions based on the SOLO taxonomy.

As expected, main effects of session, comparing the results between the pre- and the post-test, were found for most categories, namely for Remember and Understand, Apply, Analyze, and Multistructural (see Table 3.3). In all categories, students scored significantly higher in the post-test session at the end of the VEnvI curriculum than in the pre-test session, which confirms that they learned some of the concepts we taught. We furthermore found significant results regarding the type of character assignment provided for the categories Remember and Understand and Analysis.

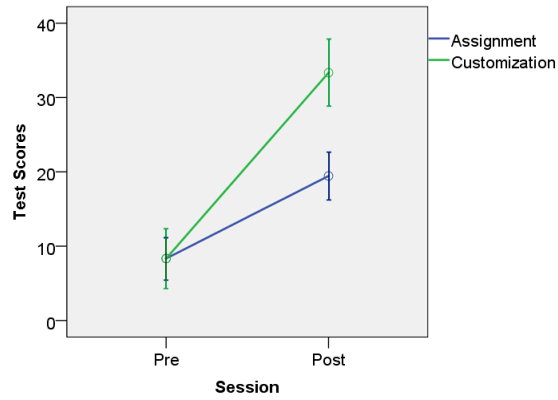


Figure 3.4: Interaction effect for Remember and Understand. Error bars represent the standard errors of the mean.

3.3.1.1 Remember and Understand

Our analysis revealed an interaction effect of session (pre vs. post) x type of character assignment (C vs. A) with $F(1, 34) = 6.54$, $p < 0.05$, and $\eta^2 = 0.161$ (see Figure 3.4.) Post-hoc comparisons with Bonferroni corrections showed that while participants in both groups improved significantly between the pre- and the post-test, participants in the Customization group increased their scores significantly more, by 25 percentage points on average from 8.33 ($SD = 17.15$) to 33.33 ($SD = 19.17$), than students in the Assignment group who only improved by 11.11 percentage points on average from 8.33 ($SD = 12.13$) to 19.44 ($SD = 13.71$) ($p < 0.05$ for all comparisons except for the results for the two groups in the pre-tests).

3.3.1.2 Analyze

In the Analyze category we found a main effect for the type of character assignment (C vs. A) with $F(1, 34) = 5.13$, $p < 0.05$, $\eta^2 = 0.131$. Participants in the Customization group ($M = 37.5$, $SD = 21.44$) scored significantly lower than participants in the Assignment group ($M = 56.94$, $SD = 29.46$) with $p < 0.05$ (see Figure 3.5 (a).) There was no interaction effect. Taking into account the main effect of session, this means that both groups improved in the questions in the Analyze category in a similar way, but students in the Assignment group were ahead of students in the Customization group to start with. Our two groups, even if the students have been randomly assigned to the conditions, therefore differed in this category from the beginning on.

Table 3.4: Significant results from the experience questions.

Statement	Scale	Pre Session M, SD	Post Session M, SD	p value	Direction
Do you feel like you are confident at dancing?	1-10	$M = 5.07$ $SD = 3.83$	$M = 6.50$ $SD = 2.81$	$p < 0.05$	UP
I want to learn more about dance.	1-5	$M = 4.21$ $SD = 0.98$	$M = 3.74$ $SD = 1.18$	$p < 0.001$	DOWN
Do you know what a computer programming language is?	0-1	$M = 0.14$ $SD = 0.36$	$M = 0.51$ $SD = 0.51$	$p < 0.001$	UP
I want to learn more about programming.	1-5	$M = 3.72$ $SD = 0.87$	$M = 3.18$ $SD = 0.76$	$p < 0.001$	DOWN

3.3.2 Experience Questions

To get insights on students' experience, we also conducted 2x2 mixed model repeated measures ANOVAs with the pre- and post-answers as a within-subjects repeated measures factor and the type of character assignment as a between-subjects factor. Again, we ensured that Box's M test of equality of covariance matrices was not significant, and Mauchly's test of sphericity was conducted.

We found main effects for four questions listed in Table 3.4. Students felt significantly more confident at dancing after the program and significantly more of them felt that they knew what a computer programming language is. However, on average they were less inclined to want to learn more about dance and programming after our program. While these results are not connected to our main questions, they give insight into the effectiveness of the VEnvI curriculum. Overall, 24 of the 36 participants gave positive comments to the VEnvI experience itself such as "It was fun."

3.3.3 Character Questions

The Character Questions included ratings but also open questions. We report our quantitative and qualitative findings below.

3.3.3.1 Quantitative Analysis

The question "How well do you like your character?", which was asked at the beginning and end of the program, was analyzed with a 2x2 ANOVA in the same way than the cognitive pre- and post-test and the experience questions. There was a main effect of session (pre vs. post) with $F(1, 34) = 5.97$, $p < 0.05$, and $\eta^2 = 0.149$. On average, participants liked their characters significantly less ($M = 5.24$, $SD = 2.41$) at the end of the VEnvI program than in the session during which the character was created ($M = 6.21$,

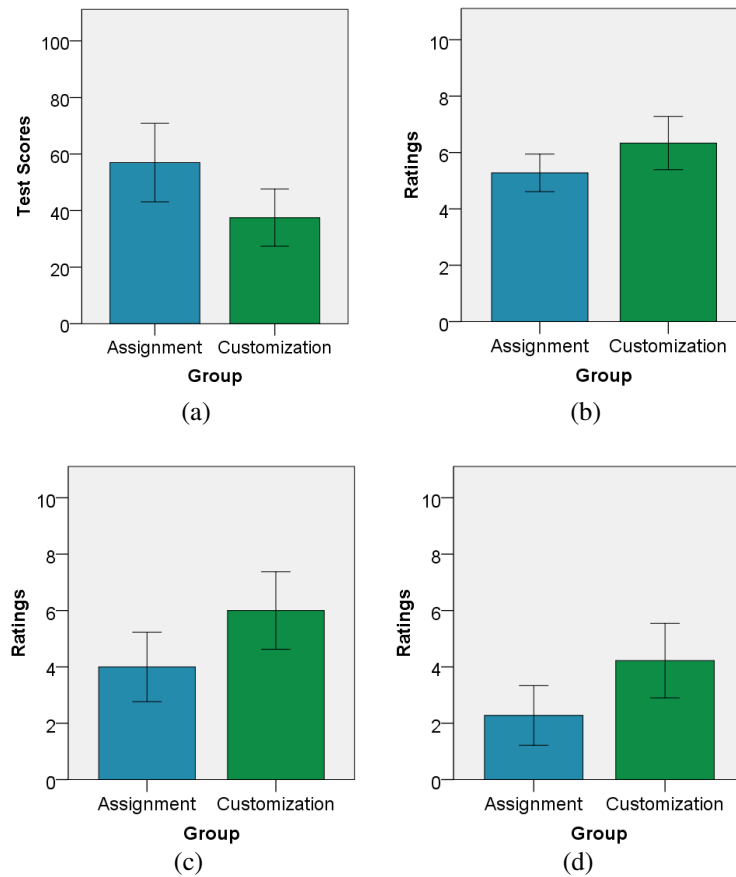


Figure 3.5: Main effects of group (Customization vs. Assignment) were found (a) for the Analyze category of the cognitive pre- and post-test and for the questions (b) “How well do you like your character”, (c) “Did the presence of others affect your decision to dance or not”, and (d) “Did you feel like the character was yourself”. Except for the first result, ratings were significantly higher in the Customization group compared to the Assignment group. Error bars represent the standard errors of the mean.

$SD = 2.08$). The analysis also revealed a main effect of the type of character assignment for this statement with $F(1, 34) = 14.26$, $p < 0.001$, and $\eta^2 = 0.30$. Participants in the Customization group ($M = 6.33$, $SD = 2.00$) scored significantly higher than participants in the Assignment group ($M = 5.28$, $SD = 1.41$), $p < 0.05$ (see Figure 3.5 (b).)

One-way between-subjects ANOVAs were conducted on questions that were only asked at the end of the program. We found a main effect of the type of character assignment ($F(1, 34) = 4.71$, $p < 0.05$, $\eta^2 = 0.122$) for the question “Did the presence of others affect your decision to dance or not?” Participants in the Customization group ($M = 6.0$, $SD = 2.91$) felt that the presence of others affected their decision to dance significantly more than participants in the Assignment group ($M = 4.0$, $SD = 2.61$) (see Figure 3.5 (c).)

For the question “Did you feel like the character was yourself?” the analysis also revealed a

significant main effect of group ($F(1, 34) = 5.30, p < 0.05, \eta^2 = 0.135$). Participants in the Customization group ($M = 4.22, SD = 2.80$) scored significantly higher than participants in the Assignment group ($M = 2.28, SD = 2.24$) (see Figure 3.5 (d).)

To investigate the type of character students created, we also asked “Did you create this character to be: yourself, a better version of yourself, a friend, a teacher, or other?” This question was inspired by Baylor et al.’s work [9]. One participant’s response was omitted because the question was left blank. Selection of the five choices was not evenly distributed in the Assignment vs. Customization groups ($p < 0.001$, Fisher’s exact test). As can be seen in Figure 3.6, students did not identify as much with their characters if it was assigned to them: no one from that group selected “yourself” and only two students selected “a better version of yourself”. None of the students chose to view their character as a “teacher.” Students who chose ‘other’ saw their characters as dancers, “a famous dancer,” random people, “a person on TV,” or “Someone I am telling what to do. Like if I was the coach and they were the student.”

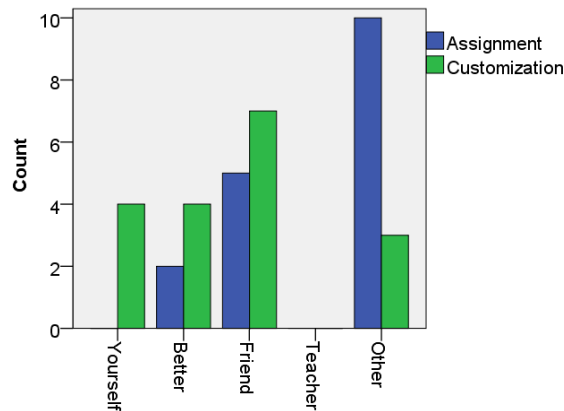


Figure 3.6: Scores for “Did you create this character to be.”

3.3.3.2 Qualitative Findings

Seventeen of the students in the Customization group allowed us to take photos of them with their characters, see Figure 3.7 for examples.

Of these students, 15 created a character with the same gender as them, 13 chose a similar skin color, 6 chose a similar hair color, and 6 chose a similar hair style. All customizable characters were changed from the default template character, which had a medium skin tone, brown boy-styled hair, and a monochromatic outfit.

Students were furthermore asked what they liked and disliked about their character. Six positive



Figure 3.7: Participants with their customized characters.

comments from students in the Assignment group mostly complimented the character's existing outfit parts like shirt or shoes. All participants in the Assignment group commented that they disliked something about the character. Of these, 8 expressed a want to have a customization system, 2 would have liked a different gender, 1 would have liked a different skin tone, 2 wanted to identify more with the character ("I was kinda hoping it would look like me and it doesn't," "I can't relate to him"), and 7 gave negative comments about the avatar's appearance ("...he's not very fashionable," "...it's pretty ugly.")

Participants in the Customization group had 9 positive comments about the characters: 8 were about appearance and 1 about being able to customize. There were 12 negative comments: Of those, 3 were not directly about the character's appearance but about the VEnvI system ("Sometimes she's hard to control, like she'll go offstage"), and 9 expressing that they wanted more customization options ("I kinda wanna change her outfit" (participants are not able to return to the customization screen and edit their characters once they are in the VEnvI dance interface), "I don't like the hair. Needs more variety of accessories, styles, and colors.") One of the students in the Customization group said, "I tried to make it me but there wasn't any way to make it look like me."

Eight of the participants gave their characters personalities, 6 of them were from the Customization group. Personalities given were positive like "a goof," and "I gave it [classmate]'s personality."

3.4 Discussion

In our results, we found multiple main effects of session, showing students' cognitive scores improved during the VEnvI program in general. Our two groups did not perform fully equally in our pre-test, but such

results can happen despite randomly assigning students to the conditions. It neither confirms nor rejects our hypothesis of higher learning outcomes in the Customization group.

We found evidence that character customization has a positive effect on learning when looking at specific categories of learning, which confirms our hypothesis. Participants who were given the possibility to customize characters learned better on Remember and Understand questions than students who were assigned characters.

Several reasons for this result are possible. Participants in the Customization group might be more attentive to the lesson. They might have felt more empathy with their character as they were given choices, as found by Turkay and Kinzer [86], or been more psychophysically alert just from having the ability to customize, as found by Lim and Reeves [39]. Participants in the Customization group liked their character more than participants in the Assignment group. They identified more with their character and also were more likely to see their character as themselves, better versions of themselves, or friends. Supporting identification with the character, over half of the Customization group students chose a character with the same gender and similar skin tone to them. Customization group students might have felt more support from their character, leading to a better learning performance.

A further finding was that students liked their character less at the end of the study than shortly after customizing it. The short duration of the customization process, animation artifacts, or unrealistic motions could explain this result. The ability to edit a character at a later point might change this finding and increase students' satisfaction with their characters over time.

Interestingly, students in the Customization group felt that the presence of others around them affected their decision to dance more than students in the Assignment group. This result points toward a lower confidence of students in the Customization group. The comments in both groups range from neutral ("I don't care what people think") to negative ("...I didn't want to look stupid"). Of the 24 participants who commented, none of the participants said the presence of others on their decision to dance was positive.

3.5 Conclusion and Future Work

In summary, we conducted a study to see how the presence or absence of character customization influenced a learning system, as well as observed participant choice of character appearance. Our main finding was that participants with customizable characters learned better in the Remember and Understand level of Bloom's taxonomy. Participants with customizable characters also liked and identified with their characters

more and were more influenced by the presence of their peers in deciding to dance.

Several further questions arise from this study: Our main finding only applies to a specific category of learning, Remember and Understand, and more studies will be necessary to understand why and if customization only improves learning effects in this category.

Previous studies have shown that some characters are more effective as pedagogical agents than others. However, given the ability to customize or select characters, students may create a character appearance that is not conducive to teaching. Future studies could investigate if people naturally build characters that would facilitate learning the most, or if it is more beneficial for learning in some cases to assign pedagogical agents.

In addition, we decided to limit our characters to virtual humans. Future work could assess learning effects on a wider range of human or non-human characters such as aliens, zombies, or animals.

Finally, our study is on specific software combining dance and computer programming concepts. More studies on different learning systems and topics would be needed to confirm if the learning effects we discovered can be generalized to other fields and systems.

Chapter 4

Study 2: Application to the Virtual Hand Illusion

In the previous chapter, we detail the initial study we conducted to expand our knowledge on the existing work of effects of model appearance and customization on learning. In this chapter, we describe the initial study we conducted to further knowledge on a different topic in the field of model appearance: the virtual hand illusion.

4.1 Introduction and Motivation

Previous research implies that any part can be taken on by the body as long as it is possible to control relevant features and behaviors of that effector. However, the question remains of if there are aspects of the VHI specific to particular model appearances. In our study, we investigate the strength of the virtual hand illusion not only for a realistic hand and very abstract representations, but also for representations with different renderings and anthropomorphic models with different sensitivities to pain.

We investigate the effects of model appearance in the context of the virtual hand illusion (VHI), a body ownership illusion (BOI) that has its roots in the rubber hand illusion (RHI). Participants play a game in an immersive virtual environment using a head-mounted display. The motions of their right hand are tracked. In the first study, participants see one of six models representing different levels of realism, different render styles, and different sensitivities to pain (see Figure 4.1) in place of their real hand. After participants block

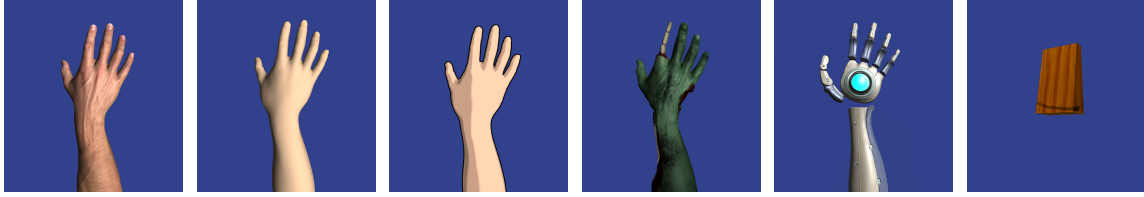


Figure 4.1: The six geometric models with distinct appearances used in this study. From left to right: realistic hand, toony hand, very toony hand, zombie hand, robot hand, wooden block.

flying spheres with their hand for three minutes in the virtual environment, a knife as a virtual threat hits their virtual hand. We measure responses towards the virtual hand being threatened with a questionnaire. In the second experiment, we study the responses of participants who are prone to the rubber hand illusion when they see and control each virtual model, one at a time, giving them the ability to compare between models. Participants block spheres for two minutes with each model in random order, and the knife hits the last model one minute and thirty seconds into the game. A questionnaire is given after each model use.

4.2 Experiment Overview

Our hypothesis is that the illusion can be shown for all hand models, but that the more realistic and sensitive to pain the model appears, the stronger the illusion will be.

We designed two experiments both using the same six controllable hand models: realistic hand, toony hand, very toony hand, zombie hand, robot hand, and wooden block (see Figure 4.1).

The first three models represent different rendered levels of realism of a human hand; the robot and zombie models were chosen as anthropomorphic representations that are non-human and have a different sensitivity to pain; finally, the wooden block was selected as an object that has no shape resemblance with a hand. All models have the same degrees of freedom except for the wooden block. The realistic hand and robot hand are free models offered through the Leap Developer Portal’s virtual reality assets. The zombie hand was modified and re-textured from the realistic hand using Autodesk Maya 2014. The toony hand and very toony hand were created by smoothing and decreasing faces on the realistic hand’s geometric model to decrease the surface detail, then changing the texture and shading; the toony hand has a tan color in place of the realistic hand’s texture, and the very toony hand furthermore has cel shading applied. The wooden block was modeled and textured using Maya 2014, and the virtual environment and games were built in Unity 4.6.2.

In both experiments, participants were placed in a virtual environment and given one of the six controllable hand models. In the first experiment, each participant experienced a single model, played a game

as a conditioning phase, was hit by a virtual knife, and was then asked to answer a questionnaire. Results showed large differences between participants, some of which experienced a strong illusion, others no illusion, independently of the model used. We hypothesized, based on these results and previous literature, that some participants are prone to the illusion while others are not. To study the effect of the different models, in a second experiment, participants were first tested to see if they experienced the RHI, then given control of the six virtual hand models one at a time.

We gathered participants' responses using a questionnaire and measured participants' physical reactions towards their virtual hand being threatened. We chose a between-subjects design for the first study, as participants can only be surprised by the threat once, and a within-subjects design for the second study to allow for model comparison despite large differences between participants.

To guarantee that our models are distinct from one another, we carried out a brief online survey. We expected participants' ratings of perceived realism and sensitivity to pain to range from highest to lowest for the six models in the order of realistic hand, toony hand, very toony hand, zombie hand, robot hand, and wooden block.

4.3 Survey on Realism and Sensitivity to Pain

4.3.1 Method

One hundred thirty-seven participants (82m, 55f) between eighteen and sixty years of age were recruited from social networking sites to volunteer for the online survey. Participants were naïve with respect to the purpose of the experiment. Participants were presented with a consent form before the survey, approved by our institution.

After preliminary demographic questions (see Appendix F), participants were presented with the six models used in the main experiments (see Figure 4.1). The models were labeled from "A" to "F". Six different orders were created randomly to avoid any ordering effects on participants' responses. Participants saw all models at the same time while answering the questions: *How realistic do you perceive hand model "A" to be?*; and *How sensitive to pain do you perceive hand model "A" to be?*. Each question was repeated for every model. Participants were asked to answer each question on a 10-point Likert scale, ranging from '1' (less realistic) to '10' (more realistic) for the realism questions, and '1' (less sensitive) to '10' (more sensitive) for the sensitivity to pain questions.

4.3.2 Results

A one-way ANOVA followed by Tukey's Q test showed significant differences between each of the hand models for perceived realism and perceived sensitivity to pain with all $p < 0.001$ with one exception, the comparison between the very toony hand and zombie hand in terms of realism. As can be seen in Figure 4.2, the order from highest to lowest realism is realistic hand, toony hand, zombie hand and very toony hand, robot hand, and wooden block. We expected the zombie hand to rate lower on realism than the very toony hand because the zombie hand belongs to a fictional character, but the zombie hand model is as detailed as the realistic hand, which may have contributed to these results. As expected, the order from highest to lowest perceived sensitivity to pain is realistic hand, toony hand, very toony hand, zombie hand, robot hand, and wooden block.

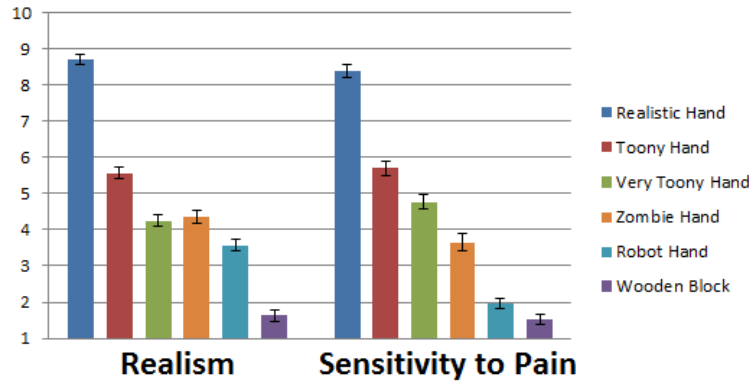


Figure 4.2: Perceived realism and sensitivity to pain of the hand models. The error bars are standard deviations of the mean.

4.4 Experiment 1

4.4.1 Method

4.4.1.1 Participants

Sixty participants (32m, 28f) between eighteen and forty years of age took part in our first experiment in exchange for a \$5 voucher. Participants consisted mainly of undergraduate and graduate students recruited from a variety of departments through fliers, e-mails, and in-class announcements. Informed consent was obtained from all participants before and after the experiment. The study was approved by our Institutional

Review Board.

4.4.1.2 Experimental Setup

Participants viewed the immersive virtual environment through an Oculus Rift head-mounted display (HMD) (see Figure 4.3). Hand tracking information was provided through a Leap motion controller mounted on the Oculus Rift. An Empatica E4 wristband was fitted to the participants' left arm. Exploratory EDA was recorded, but too many recordings yielded values outside of expected ranges to allow for quantitative analysis and were thus discarded. Participants sat at a table during the study so they had a place to rest their elbows if they needed to. The level of the plane in the virtual environment was adjusted to correspond to the real table.

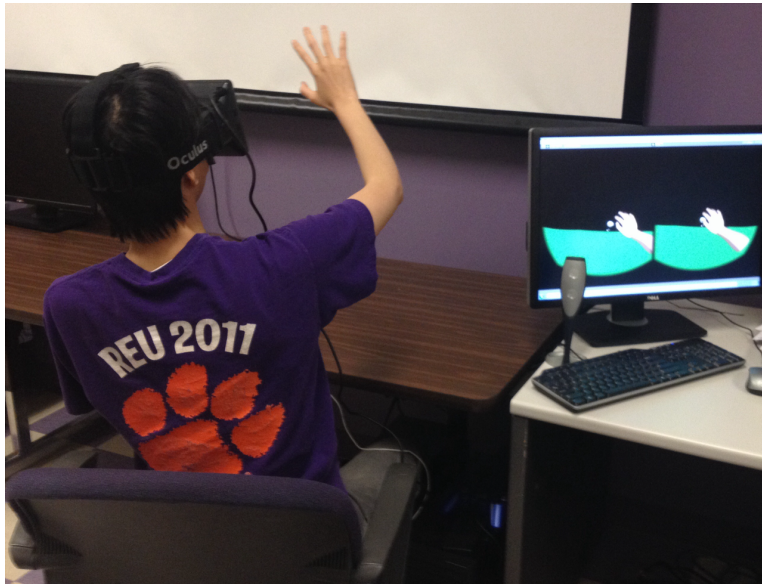


Figure 4.3: The immersive virtual environment was viewed through an Oculus Rift. A Leap motion controller mounted to the Rift tracked the right hand.

4.4.1.3 Design

The study had a between-group design, with ten participants in each group. The independent variable, the virtual model in place of the hand, was randomly selected for participants before they entered the immersive virtual environment. The main dependent variable in this study is the strength of the virtual hand illusion, measured with questions testing ownership and implications or signs of ownership. We furthermore ask questions about pain, realism, and immersion.

4.4.1.4 Procedure

After filling out an initial demographic questionnaire (see Appendix F), participants were placed in the immersive virtual environment. Upon wearing the Oculus Rift, they were asked to keep the left arm stationary and raise the right arm in front of the Rift to view and control the model.

Participants were then asked to take as much time as needed to become used to the model and the environment, a black sky with a green plane. Once participants were comfortable with the setup, they were asked to play two short games. In the first game, participants need to block white, slowly approaching spheres for three minutes. The spheres explode both visually and with a short sound effect if they collide with the virtual model (see Figure 4.4). The speed of the spheres doubles in the middle of the game. Participants could prop their elbows on the table if they felt tired, but were asked to keep their hand and arm on screen. This first game serves as a conditioning phase to get participants accustomed to the virtual hand and to create the body ownership illusion [3, 29, 95].

The second game is a threat stage: a knife comes down at the virtual hand without warning (see Figure 4.4). This threat was chosen based on Ma and Hommel's study [49]. When participants were ready for game two, they were asked to keep the model on screen, and a few seconds passed before the virtual knife came down on the model. Upon impact, a slicing sound effect occurred and blood started dripping from the model. After ten seconds, the participant was asked to remove the virtual reality equipment and complete a questionnaire regarding the virtual hand illusion.

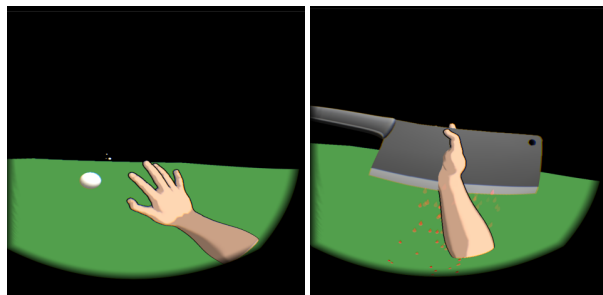


Figure 4.4: The ball game (left) serves as the conditioning phase of the study. The knife (right) hits the model.

4.4.1.5 Questionnaire

The dependent variables were measured by the participants' answers on a survey (see Table 4.1) after the virtual environment experience. Versions of the standard Botvinick and Cohen 9-question survey altered for the virtual hand illusion by Ma and Hommel and by Yuan and Steed [13, 49–51, 95] have been adapted for

this experiment. For each statement, participants chose a rating on a seven-point Likert scale ranging from 1 for "strongly disagree" to 7 for "strongly agree." At the end of the experiment, participants were also asked to write down any comments they had about their experience. The full questionnaire is displayed in Appendix G and Appendix H.

4.4.2 Results

One of our first observations when analyzing the results is that many of the statements show surprisingly large ranges and variances in their answers, often including the full range or nearly the full range of possible answers from strongly disagree to strongly agree in each condition. Since a range of 6 is the maximum possible value, a range of 4 for a specific statement and condition indicates clear disagreement among participants. For each statement, the average of the ranges of the six conditions is larger than 4 except for statement Q-A4. Five of the statements even have average ranges larger than 5. One interpretation of these results is that the illusion is strong for some participants and does not work at all for others.

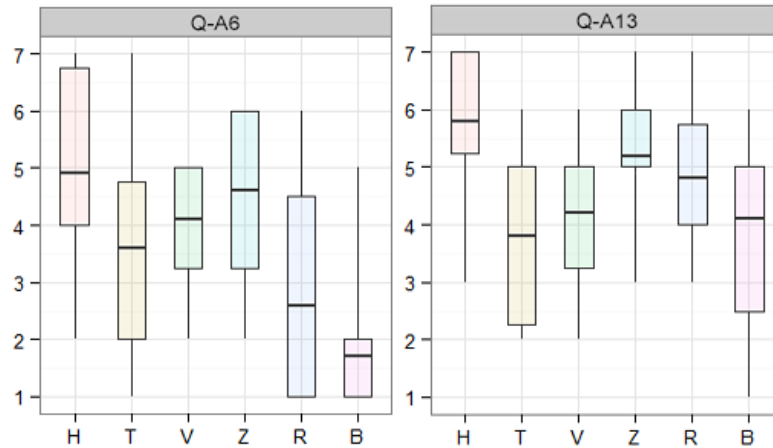


Figure 4.5: Boxplots of the questionnaire results with significant effects. H stands for the human or realistic model, T is for toony, V for very toony, Z for zombie, R for robot, and B for wooden block. The full statements can be seen in Table 4.1. The boxes indicate inter-quartile ranges and the bars show the range of the ratings.

Shapiro-Wilk's W test shows that many of the distributions are not normal. The results to the questionnaire were therefore analyzed for differences between conditions using Kruskal-Wallis tests with the appearance of the virtual hand as the independent factor (between-subjects variable with the six values realistic human, toony, very toony, zombie, robot, and wooden block or H, T, V, Z, R, and B, respectively). Mann-Whitney U tests with a significance level of 0.05 were used on selected comparisons. Significant differences between conditions were found for statement Q-A6 ($H(5,60)=20.02$, $p<0.01$), where participants'

disagreement with the block beginning to resemble their own hand was significantly stronger than for the realistic hand, toony hand, very toony hand, and zombie hand and participants' disagreement was also significantly stronger when using the robot hand than with the realistic hand or the zombie hand; and for statement Q-A13 ($H(5,60)=12.20$, $p<0.05$), where the realistic hand was perceived to be significantly more realistic than the toony hand, very toony hand, and wooden block and where the toony hand was also perceived to be significantly less realistic than the zombie hand (see Table 4.1 and Figure 4.5).

The comments at the end of the questionnaire yield some interesting insights. One participant in the wooden block condition wrote, "It seemed real at points and I felt my palm opening to catch the ball". Another one in the same condition said that "about 2/3 of the way through the 1st level, it started to feel like I was actually blocking the balls." Other participants commented on the knife: "The knife was scary and unexpected. I kept trying to shake it off and save my hand" (toony hand condition). "I definitely felt something in my arm, like it had been pinned to the table." (zombie hand condition). However, some participants did not feel any effect: "The hand in the virtual reality seemed to move and look much like my hand [...]. When the knife fell, however, I did not feel any sensations which caused me to believe that it had fallen on my actual hand." Finally, ten participants (three each in the realistic, very toony, and robot conditions, one in the zombie condition) commented about the hand disappearing at some point or the fingers moving unrealistically, for example, "Sometimes, when I would move my thumb a certain way or make a fist, my thumb went through my other fingers."

4.4.3 Discussion

Only two statements showed significant differences between the hand models, Q-A6 and Q-A13, and both of these are not core statements related to the illusion. Interestingly, in Q6, the zombie hand model, green with bones protruding and pieces of flesh missing, is grouped with the other organic models (human, toony, and very toony) in that participants think it begins to resemble their own hand significantly more than the robot hand and block.

In this first experiment, we cannot support our hypothesis that the VHI is stronger for models perceived as more realistic and sensitive to pain. In all of the conditions, some participants strongly agreed with the statements. Based on this, we can conclude that the illusion can happen with all of the tested models. There are trends showing the possibility that the VHI is weakest for the wooden block and strongest for the realistic and the zombie hand shapes. We run a second study, allowing each participant to experience all the models, to further investigate these observations.

Table 4.1: Questionnaire and results of our first study. Corresponding concepts in bold belong to core statements designed to test if the virtual hand illusion is occurring; they are either direct ownership questions, or implications or signs of ownership. Kruskal-Wallis tests were used to test for significant results. The mean and standard deviation over all models is provided when no significant differences were found. Results are reported based on Mann-Whitney U tests.

Questionnaire Item	Corresponding Concept	Mean, Standard Deviation	Results
Q-A1: Sometimes I had the feeling that I was holding a real ball	Intersensory interactions	(3.45, 1.63)	
Q-A2: I had the sensation that I felt the knife on my hand in the same location where the virtual hand/block on the screen was in contact with the knife	Location-related similarity	(3.11, 1.99)	
Q-A3: I felt like the sensation I felt on my hand was caused by the contact of the knife with the virtual hand/block on the screen	Intersensory interactions	(2.95, 2.04)	
Q-A4: The movements of the virtual hand/block on the screen were caused by myself	Agency	(6.32, 1.07)	
Q-A5: It sometimes seemed my own hand was located on the screen	Location-related similarity	(5.58, 1.61)	
Q-A6: The virtual hand/block on the screen began to resemble my own hand, in terms of shape, skin tone, freckles, or some other usual feature	Visual similarity	H = (4.90, 1.91) T = (3.60, 2.12) V = (4.10, 1.28) Z = (4.60, 1.71) R = (2.60, 2.01) B = (1.70, 1.25)	H, T, V, Z > B; H, Z > R
Q-A7: Sometimes it seemed as if what I was feeling was caused by the knife that I was seeing on the screen	Intersensory interactions	(3.10, 1.85)	
Q-A8: Sometimes I felt as if the virtual hand/block on the screen was my own hand	Ownership	(5.17, 1.53)	
Q-A9: Sometimes I felt as if my real hand was becoming virtual	Filler or control	(4.28, 2.15)	
Q-A10: It seemed as if I might have more than one right hand	Filler or control	(2.12, 1.44)	
Q-A11: I anticipated feeling pain from the knife on the screen	Pain	(2.73, 1.81)	
Q-A12: During the experiment there were moments in which it seemed that my own hand was being hit by the knife	Ownership	(2.91, 1.88)	
Q-A13: I thought the virtual hand/block on the screen looked realistic	Realism	H = (5.80, 1.40) T = (3.80, 1.47) V = (4.20, 1.32) Z = (5.20, 1.32) R = (4.80, 1.23) B = (4.10, 1.14)	H > T, V, B; Z > T
Q-A14: I was so immersed in the virtual reality, it seemed real	Immersion	(4.53, 1.58)	

4.5 Experiment 2

4.5.1 Method

4.5.1.1 Participants

Fifteen participants (14m, 1f) between eighteen and forty years of age took part in the second experiment in exchange for a \$5 voucher. As in the previous experiment, participants consisted mainly of students and the study was approved by our IRB.

4.5.1.2 Experimental Setup and Design

This experiment had a within-group design to allow participants to make direct comparisons among the different models. It first consisted of a pre-test, displayed in Appendix I, to see if participants could experience the rubber hand illusion. Afterwards, it used the same equipment and setup as the first study. The order of the six virtual models in place of the hand, the independent variable, was randomly generated for each participant before entering the immersive virtual environment. The dependent variables are the same as in the first study, with a slightly adapted and shortened questionnaire.

4.5.1.3 Procedure

After filling out an initial demographic questionnaire, participants were seated at a table emulating Botvinick and Cohen [13]’s setup. Participants placed their left hand behind a barrier on the table obstructing their view. A life-sized rubber model of a left hand was placed in front of them. Two paint brushes were used to stroke the rubber hand and real hand synchronously for two minutes. The participant then filled out a short questionnaire that allowed us to find out if the participants felt the illusion.

Then, participants were placed in the immersive virtual environment in the same way as in the first experiment. Upon wearing the Oculus Rift, they were asked to keep the left arm stationary and raise the right arm in front of the Rift to view and control the model.

Once participants were comfortable with the setup, they were asked to play two-minute game sessions using different hand models, with the goal of blocking objects that come their way. The speed of the spheres remains constant through the entire game. The knife only drops on the last model. After every game session, participants were read statements and asked to choose a rating on the seven-point Likert scale, ranging from 1 for ”strongly disagree” to 7 for ”strongly agree.” The statements (see Table 4.2) were adapted from the

questionnaire in Experiment 1, and the full questionnaire is displayed in Appendix J.

4.5.2 Results

The RHI did not occur for three participants, so their data was excluded from the analysis. The results to the questionnaire were analyzed for differences between conditions using the Friedman test and Wilcoxon tests where necessary with the appearance of the virtual hand as the independent factor (within-subjects variable with the six values realistic, toony, very toony, zombie, robot, and wooden block or H, T, V, Z, R, and B, respectively).

Significant effects with $p < 0.05$ were found for all statements except for Q-B2 ($p \approx 0.18$) corresponding to agency and statement Q-B6, which was only significant at the 0.1 level with $p \approx 0.068$ (see Table 4.2 and Figure 4.6). As there are no standard posthoc tests for Friedman tests, we used Wilcoxon tests on selected comparisons with $p < 0.05$ as significance level. Nearly identical results were found when using a Newman-Keuls posthoc.

Participants rated the wooden block significantly lower than all other models in four of six of the core statements, those corresponding to location-related similarity and ownership. The zombie hand was rated significantly lower than the human, toony, and very toony hand in one ownership question (Q-B5), and the zombie, very toony, and block hand were rated significantly lower than the human hand in another ownership question (Q-B7). For question Q-B4 corresponding to visual similarity, there was a significant effect of the virtual hand beginning to resemble participants' hands with the human, very toony, and toony hands being rated highest, followed by the robot and zombie hand as a second group, then the block with the lowest rating. For intersensory interaction, participants said that what they were feeling was caused by the ball significantly less often when using the block model than when using the realistic human model (Q-B6). In terms of realism (Q-B8), the block was rated significantly less than all other models for looking like a realistic virtual hand, and the human hand had a significantly greater rating than all models except for the toony hand. Finally, participants rated the block significantly lower than all other models for making them feel immersed in virtual reality.

Verbal comments at the end of this study gave interesting insights as well. Several participants said they would have felt more connected to the hand if it had moved synchronously with their own hand at all times or if the model did not disappear sometimes during the study. One participant said, "I want to ask what you are using for the heat haptics. I felt a heat sensation where the ball hits me. Every time a ball hit." There were also some interesting comments regarding the non-human hands. One participant said, "The robot hand and wood

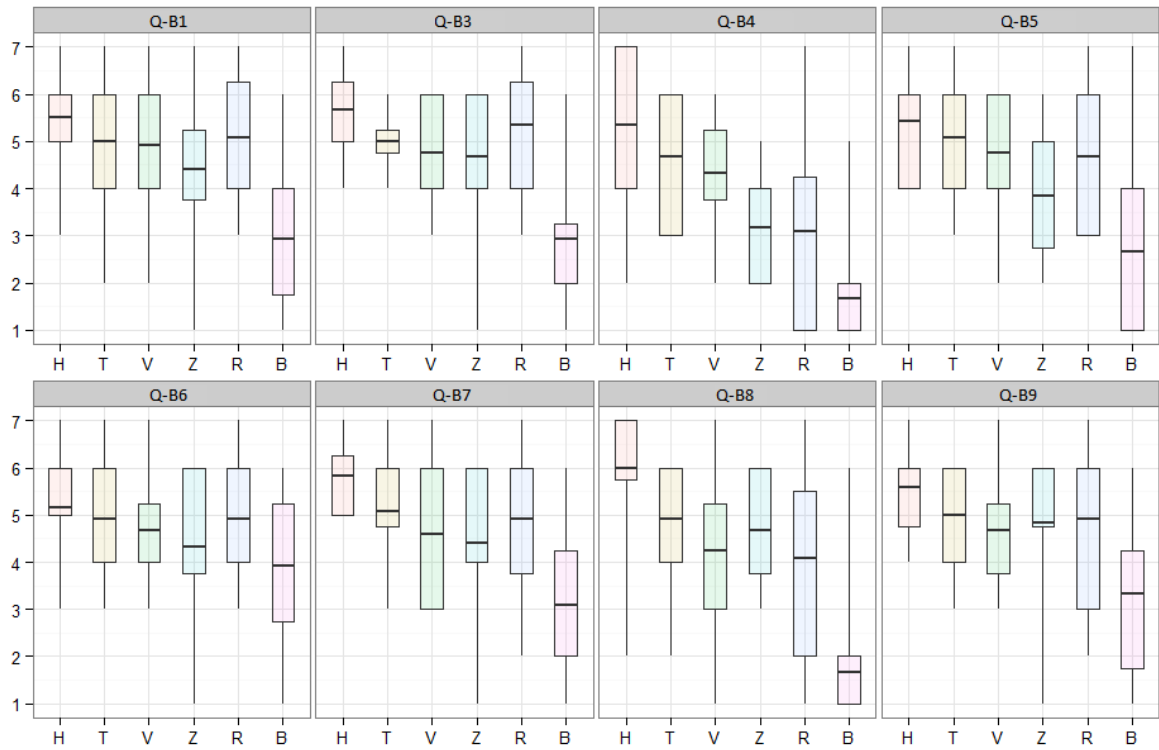


Figure 4.6: Boxplots of the questionnaire results with significant effects. H stands for the human or realistic model, T is for toony, V for very toony, Z for zombie, R for robot, and B for wooden block. The full questions can be seen in Table 4.2. The boxes indicate inter-quartile ranges and the bars show the range of the ratings.

were disconnected from me...I would have gotten more of a shock [if the knife had hit one of the human-like hands].” One participant with the zombie hand being threatened by the knife said, ”I was having fun inspecting the hand, but I [also] didn’t want to look at the zombie hand (because it appeared he was wounded).” It seems that all participants who experienced the RHI were also able to experience the VHI. Of the three participants who were omitted as they did not experience the RHI, only one rated the VHI consistently low throughout the entire study: ”I didn’t feel anything. I mean, I knew I was playing a video game the whole time.”

4.5.3 Discussion

In summary, participants’ ratings were significantly lower for the block model compared to every other model in seven of the nine questions. We can therefore confirm our hypothesis that participants felt that the VHI was weaker when using the wooden block model than when using any other model. Furthermore, participants’ ratings were significantly higher for four of the questions when the realistic human model was used compared to some of the other models, not taking the block model into account. We conclude out of this result that participants did have a preference for the high realism of that model. The other models can be ranked in between with some differences, such as the zombie model rated less than the toony and very toony models in two questions. However, those differences would need to be investigated further. We also found that appearance does not affect agency. For the three omitted participants, it is unclear if they were not prone to the RHI or needed longer than two minutes for the illusion to take effect: only one of them did not experience the VHI at all. Our observations that the VHI occurs for more participants than the RHI supports Ma and Hommel [51]’s findings that being able to control a model is more convincing than seeing and ’feeling’ an immobile model being touched.

4.6 Conclusion and Future Work

We investigated the effect of hand model appearance on the VHI. The first study, using a between-subjects design, yielded no significant differences for the core statements. Yet, the VHI was felt for all models to some extent. The second experiment, using a within-subjects design, had significant differences.

Our findings suggest that there are large differences between participants leading to a large error variance, but in direct comparison, anthropomorphic models lead to a stronger illusion and a realistic human model leads to the strongest effects. Appearance does not affect agency, and the illusion can happen for all models. Even a wooden block that was used instead of a hand lead to comments that showed an effect of

illusion for some of the participants.

Our results on ownership are overall consistent with all studies mentioned in Table 2.1, but our results on agency contrast to Argelaguet et al. [2]'s findings that agency is stronger for less realistic virtual hands. Based on the comments of some participants, the illusion might have been reduced in some cases as the hand and especially finger motions were not captured perfectly at all times despite restricting the area in which the spheres arrive. Yet, this and experiencing all the models in direct comparison do not seem to deter participants from feeling like they control any sort of hand.

Another explanation for the VHI effects in the second experiment could be that participants gauge danger in virtual surroundings by context: "That robot hand...Maybe I would have felt something [from the knife] if [the hand] looked more real; there was blood so it didn't." One participant commented that the human-looking hand models did not move as well as the robot hand, and one participant said, "there's more of a suspension of disbelief [for the robot and zombie hands] so I feel like it's more real. I picked at [the hand model] the more it looked [like a human hand]." These comments suggest that the participants are more critical of models nearing their own hands. However, the human hand still rated the highest across participants in general for the VHI, suggesting that such an aesthetic is not detrimental to immersion.

Further investigation will be needed to fully understand the illusion in virtual environments and the effect of realism on it. How would BOIs be influenced by more realistic environments or nearby interactive characters?

Our results and the large variances between participants' ratings are consistent with prior research, which has shown that the VHI is only convincing for some participants. An interesting next step would be to investigate the reasons behind this observation. Are some people more prone to the illusion? Does the length of the induction phase influence the results? Would the elimination of lag and non-accurate tracking increase the effects? Future work will need to address these questions.

Table 4.2: Questionnaire and results of our second study. Corresponding concepts in bold belong to core statements designed to test if the virtual hand illusion is occurring; they are either direct ownership questions or implications or signs of ownership. Friedman tests were used to detect significant differences, which were found for all statements except for Q-B2. The mean and standard deviation over all models is provided when no significant differences were found. Results are reported based on Wilcoxon tests.

Questionnaire Item	Corresponding Concept	Friedman test	Mean, Standard Deviation	Results
Q-B1: I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.	Location-related similarity	$\chi^2(5) = 17,78$	H = (5.50, 1.09) T = (5.00, 1.54) V = (4.92, 1.51) Z = (4.42, 1.83) R = (5.08, 1.44) B = (2.92, 1.78)	H, T, V, Z, R > B
Q-B2: The movements of the virtual hand on the screen were caused by myself.	Agency	$\chi^2(5) = 7,58$	(6.06, 0.95)	
Q-B3: It sometimes seemed my own hand was located on the screen.	Location-related similarity	$\chi^2(5) = 24,33$	H = (5.67, 1.07) T = (5.00, 0.74) V = (4.75, 1.14) Z = (4.67, 1.50) R = (5.33, 1.37) B = (2.91, 1.68)	H, T, V, Z, R > B
Q-B4: The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.	Visual similarity	$\chi^2(5) = 36,19$	H = (5.33, 1.72) T = (4.67, 1.37) V = (4.33, 1.44) Z = (3.17, 1.19) R = (3.08, 2.07) B = (1.67, 1.23)	H, V, T > R, Z > B
Q-B5: Sometimes I felt as if the virtual hand on the screen was my own hand.	Ownership	$\chi^2(5) = 23,29$	H = (5.42, 1.16) T = (5.08, 1.16) V = (4.75, 1.36) Z = (3.83, 1.40) R = (4.67, 1.56) B = (2.67, 1.92)	H, T, V, Z, R > B; H, T, V > Z
Q-B6: Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.	Intersensory interactions	$\chi^2(5) = 10,28$	H = (5.16, 1.19) T = (4.91, 1.24) V = (4.67, 1.15) Z = (4.33, 1.67) R = (4.92, 1.44) B = (3.91, 1.73)	H > B
Q-B7: During the experiment there were moments in which it seemed that my own hand was catching the ball.	Ownership	$\chi^2(5) = 27,51$	H = (5.83, 0.83) T = (5.08, 1.08) V = (4.58, 1.16) Z = (4.42, 1.62) R = (4.92, 1.62) B = (3.08, 1.68)	H, T, V, Z, R > B; H > V, Z, B
Q-B8: I thought the virtual hand on the screen looked realistic.	Realism	$\chi^2(5) = 27,62$	H = (6.00, 1.48) T = (4.91, 1.24) V = (4.25, 1.76) Z = (4.67, 1.23) R = (4.08, 2.23) B = (1.67, 1.44)	H, T, V, Z, R > B; H > V, Z, R, B
Q-B9: I was so immersed in the virtual reality, it seemed real.	Immersion	$\chi^2(5) = 24,60$	H = (5.58, 1.08) T = (5.00, 1.20) V = (4.67, 1.30) Z = (4.83, 1.53) R = (4.92, 1.73) B = (3.33, 1.83)	H, T, V, Z, R > B

Chapter 5

Study 3: Application to the Virtual Hand Illusion II

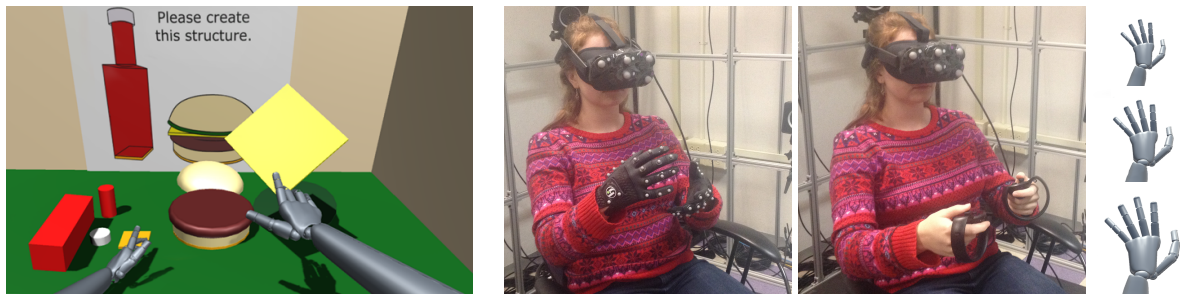


Figure 5.1: In our experiment, participants complete block stacking puzzles in virtual reality (left), controlling their avatar’s hands either with tracked gloves (middle, left) or with touch controllers (middle, right). The avatar’s hands are varied to fit the participant’s hands in size or to be 25% larger or smaller (right).

In the previous chapter, we describe the initial study we conducted on model appearance in the virtual hand illusion to contribute to our knowledge in the field. In this chapter, we describe a final study to further observe two details of the virtual hand illusion: hand model size and interaction modality.

5.1 Introduction and Motivation

The cortical homunculus is the representation of the human body in the brain: it is a mapping of body locations to brain locations. Humans have a flexible representation of their bodies. They are able to control and feel ownership of avatars that do not resemble them. The ability to move and use discrepant

bodies is a phenomenon termed homuncular flexibility [38] because it evidences the adaptability of the mental representation of the body in the brain. Experiments on homuncular flexibility such as giving subjects a controllable tail [82] or using arms to control legs [91] initially appear to have frivolous purposes, but they also open the important question of how to best tailor virtual reality bodies, user interfaces, and applications suited to medical, training, and educational fields to the limits (or lack of limits) in our minds.

The feeling that a body or body part belongs to oneself has been termed the body ownership illusion. Feeling that a rubber or otherwise fake hand belongs to oneself has been termed the rubber hand illusion, and the feeling of ownership for virtual hands is subsequently the virtual hand illusion. Body ownership illusions are similar to homuncular flexibility, but have a different neural basis. The brain can be easily tricked into feeling ownership over virtual limbs that do not belong to one's body [13]. Despite the extensive investigation on both the body ownership illusion and homuncular flexibility, there are still many questions that remain unanswered. For example, to what degree does a body part of unusual size influence perception and action? Lanier and colleagues at VPL Research pioneered some of the first informal studies on virtual worlds in which people could interact with each other [38]. He found through a bug that caused avatars' virtual hands to become gigantic, "like a web of flying skyscrapers," that people could learn quickly to control unusual bodies. This initial event was one inspiration for us to ask: with the simple change of relative hand size, what will people experience differently while completing tasks in a virtual environment? Most games or other applications with self avatars give users an unchangeable virtual body that does not correspond to each person's individual size. While previous studies have shown that experiencing the body ownership illusion with different sized body parts in virtual reality is possible, they do not take into account questions such as, do users have a preference for unaltered versus unusual sizes? Are discrepancies in body size disruptive to virtual experiences beyond influencing the ability to measure objects in comparison to the virtual body? Thus, we explore if it is important to adjust the avatar size to fit everyone, or acceptable to use a one-size-fits-all approach.

In addition, technology is moving towards allowing new ways to interact with virtual environments. The default interface with virtual reality has been with controller and device inputs such as buttons and keyboards, but in recent years has extended to motion tracking body parts, allowing people to have the freedom of not physically holding a device while interacting. However, this is at the expense of haptic feedback. Current commercial virtual reality applications allow tracking of hands, but little research has been conducted on user preference for motion tracked body parts versus controller input. This is the motivation for our interaction modality condition: we would like to explore how people perceive their virtual hands if they can directly control them versus using game controllers.

As the modality and hand size could potentially influence each other, our study observes both variables at the same time. Both variables are relevant to the current development of virtual reality systems. We are interested in knowing more about how these conditions affect factors such as efficiency and fun. Thus, we conduct an experiment in a virtual environment with interactive puzzles to explore these questions (see Figure 5.1).

5.2 Experiment Overview

5.2.1 Overview and Design

The goal of our experiment is to investigate the effects of hand model size and interaction modality on the virtual hand illusion. Ownership is the dependent variable that provides evidence of the virtual hand illusion. We furthermore explore the effects of hand model size and interaction modality on agency, realism, immersion, efficiency, performance, likability, fun, perceived size, and preference.

We observe how participants perceive virtual hands if the hand models are controlled directly by their own hands or with Oculus Touch controllers (Glove vs. Controller), and if the models are smaller than, fitted to, or larger than their hand (Small vs. Fit vs. Large). The interaction modalities are shown in the two center panels of Figure 5.1. To track the hands, we offer different sizes of motion capture gloves. The Fit hand size is created from the motion capture gloves that best fit each participant. In the Small and Large hand conditions, the virtual model is respectively 25% larger or smaller than the participants' glove fit. In the Glove condition, participants can pick up virtual blocks by grasping them. Their hand motions are tracked and displayed on the virtual hands. In the Controller condition, participants press buttons with their thumbs and index fingers to grasp blocks. The virtual hand model will imitate a corresponding pinch when the buttons are pressed.

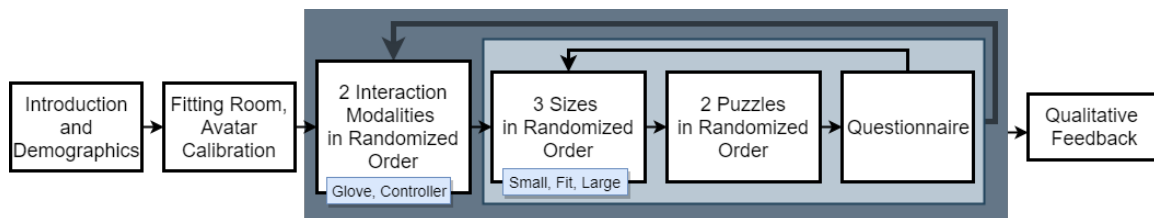


Figure 5.2: Overview of our study procedure. Participants begin with an introduction and demographic questionnaire. In VR, the avatar is calibrated to fit their body. For the experiment, participants complete each of 12 puzzles using either the glove or touch interface and with either small, fit, or large sized hands. At the end, we ask participants for qualitative feedback.

Our study uses a 2x3 within-subjects design to observe all conditions in direct comparison. The independent variables are the interaction modality (Glove vs. Controller) and the virtual model hand size (Small vs. Fit vs. Large). The main dependent variable is ownership, which indicates the strength of the virtual hand illusion.

An overview of our study procedure is shown in Figure 5.2. The experiment consists first of a fitting room to adjust the avatar's size to participants, then of two sessions of interaction modality presented in randomized order. In each session, we allow participants to assemble two puzzles with each hand size condition, and after each condition we give the study questionnaire. We furthermore record gameplay data. The hand sizes are presented in randomized order. In addition, each puzzle is shown only once, and which puzzle has to be solved in which condition is also randomized. This results in a total of 6 conditions (2 interaction modalities x 3 hand sizes) and 12 trials since there are 2 puzzles for each condition. Afterwards, we ask participants about their experience to gather qualitative feedback.

Our hypotheses are:

- The virtual hand illusion is stronger for participants in the Glove condition.
- The virtual hand illusion is stronger for participants in the Fit hand condition.

5.2.2 Experimental Setup

Participants sit in a chair with a small table in front of them, surrounded by an OptiTrack motion capture system consisting of 16 cameras as illustrated in Figure 5.3. They view the virtual environment through an Oculus Rift head-mounted display (HMD).

Participants control a free robot model offered through Unity's 4.0 Mecanim Animation Tutorial.¹ The avatar is modified using Maya 2017 and Unity 5.6.1 to have resizable hands. We hide the avatar's head so that the participant can look down and see their virtual body without the head geometry obscuring it. The avatar hand has all the degrees of freedom for movement of the twenty finger joints, but does not perform subtler movements such as skin stretching and being able to flex the palm. The avatar is placed in a virtual room, which is a simple environment modeled using Maya 2017. Textures are created with Adobe Photoshop CC 2017 and PaintTool SAI. The scenes are built in Unity 5.6.1.

The experiment puzzles (see Figure 5.8) are created with blocks of a variety of shapes and sizes to simulate the potential diversity of objects people handle on a daily basis. When new puzzles are introduced,

¹<https://www.youtube.com/watch?v=Xx21y9eJq1U>

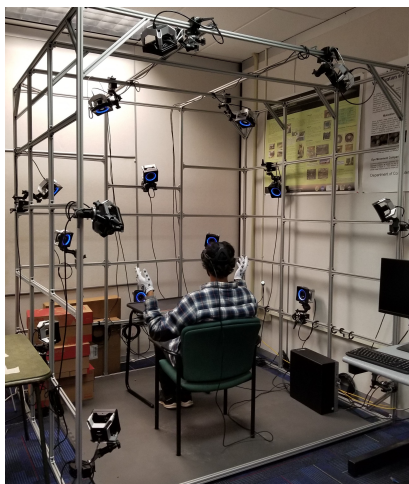


Figure 5.3: Experimental setup. Participants sit in the middle of a motion capture system at a small table. The placement of the cameras is optimized for capturing the small markers on each glove.

their blocks are randomly distributed in reachable space in front of the participants. Blocks turn semi-transparent when they are within reach of being picked up, and make a small noise when they are picked up. When a block comes into contact with another block it needs to be stacked on to progress the puzzle, the bottom block highlights in green; letting go of the held block then allows it to be snapped into place with a clicking noise. We also chose to not implement gravity so participants would not lose blocks easily, so if a block is let go of in mid-air, it stays in place until picked up again.

When a participant begins the virtual experiment, we first place them in a calibration area, where the avatar is adjusted to fit their body. We support resizing the torso, arms, palms, and fingers through the use of resizers, prismatic joints which can change the offset from their parent without distorting the avatar's skin (see Figure 5.4). The torso and arm sizes are estimated based on the participant's T-Pose while seated in the chair, and can be manually adjusted by the experimenter.

The hand sizes are determined by the glove size worn by the participant. The lengths from wrist to middle fingertips of the gloves range from 15cm to 21.5cm, and each glove is associated to a pre-saved avatar hand size. Figure 5.5 shows the ranges of available scales as well as how the hands change for each glove. Sizes are determined based on manual measurements taken from the gloves. Both the Glove and the Controller condition use the same hand models.

The avatar's upper body is animated based on the hand positions. The wrists follow the base of the hands using 2-link analytical inverse kinematics (IK) up to the avatar's shoulders. If the arms cannot reach the input positions, the torso leans to satisfy the reach.

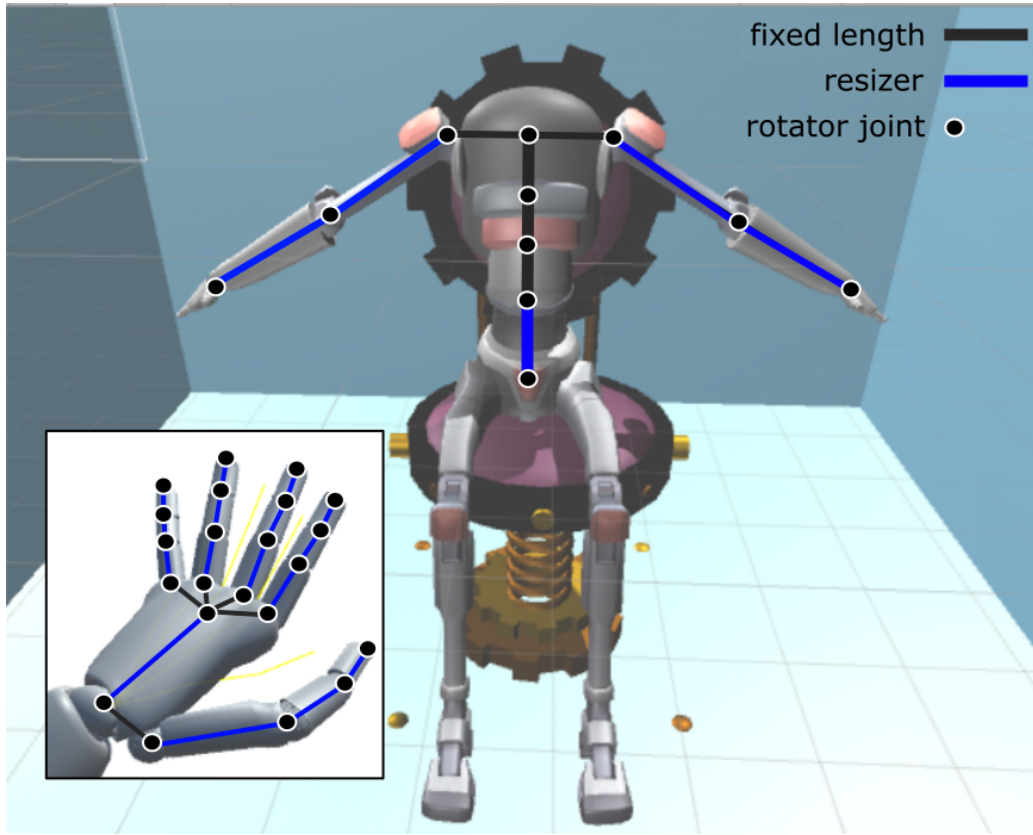


Figure 5.4: Virtual character in our fitting room. We use resizers, shown in blue, to change the size of the avatar’s arms, torso, and hands to match the participants without distorting the skin. Rotational joints, shown as circles, are used to change the pose.

We animate the hands using either tightly fitted gloves and an OptiTrack motion capture system or using Oculus Touch controllers. Each glove is tracked with 19 markers placed between the joints as seen in Figure 5.6. Participant hand poses are captured following Han et al.’s approach [24]. The resulting data, the first 3 joints of each finger along with global positions for each finger tip, is streamed to our virtual environment over a network connection. For the avatar’s hands, the thumbs follow the finger tip using 3-link analytical IK. The avatar’s fingers match the orientation of the streamed fingers.

We use marker positions of the HMD headset to align the motion-capture system with the Oculus system. To animate the hands with the touch controllers, we hard-code finger poses based on button presses. Pressing buttons under the thumbs makes the thumbs close, and pressing buttons under the index fingers makes the index fingers close. Pressing the buttons for the thumb and index fingers together creates the grasping pose that allows to pick up blocks.

To detect grasping and releasing hand gestures in the glove condition, we estimate the velocity

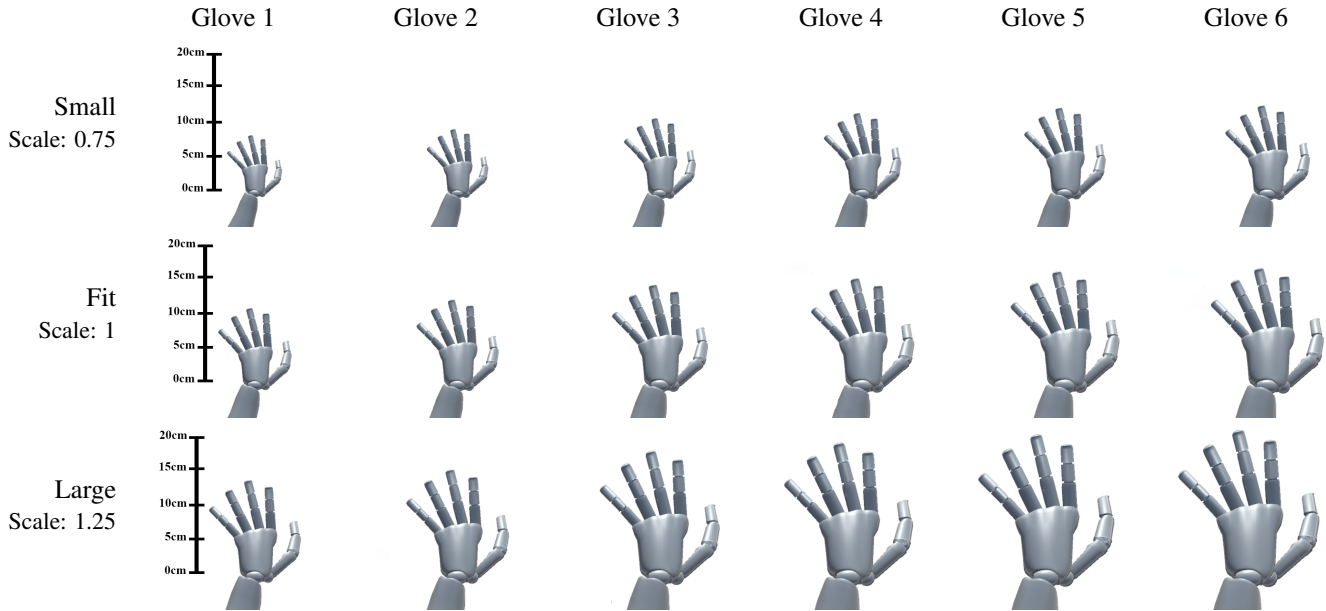


Figure 5.5: Experiment hand model displayed as a function of the motion capture glove worn by the participant (Figure 5.6). The scale 1 hand corresponding to glove 4 matches the model sent to our system. All other glove sizes are scaled relative to glove 4 based on the average finger lengths of each glove size (measured manually). The hand displayed in the Fit condition corresponds to the participant’s glove size. The hand displayed in the Small condition is 75% of the fit glove size. The hand displayed in the Large condition corresponds to 125% of the fit glove size.

between the index and thumb positions and test whether it is greater than a given threshold. This threshold is a function of the hand-size, so that the grasping experience is the same regardless of glove size. We use exponential smoothing so that small fluctuations in position do not trigger a grab or release. Both the Glove and Controller conditions allow users to drag blocks by simply pinching their index and thumb fingers together. In practice, participants use all fingers to grab.

5.2.3 Participants

Twenty participants (12 male, 8 female; ages between 18 and 40) volunteered for our study. Participants consisted mainly of undergraduate and graduate students recruited from Clemson University. Nineteen of our participants were right-handed and one was left-handed. One participant wore our size 2 gloves, four wore size 3, three wore size 4, nine wore size 5, and three wore size 6. We obtained informed consent from all participants before the study following the guidelines set by our Institutional Review Board. Participants received a \$5 voucher for their time.



Figure 5.6: The motion capture gloves used in our study. Each glove has 19 markers, with finger markers being placed between joints. In the Glove condition, we receive global wrist positions and orientation along with the poses of fingers.

5.2.4 Procedure

After filling out an initial demographic questionnaire (see Appendix K), participants put on motion capture gloves in their size and are seated in the motion capture system.

Wearing the Oculus Rift places participants in the virtual fitting room. Participants are asked to hold out their arms in a T-pose for the motion capture gloves to track and scale the avatar's arm length to theirs, then place their arms in their lap for scaling the avatar torso to their height. Then, the main experiment scene is started.

Participants are asked to take as much time as needed to become comfortable with the virtual environment, a small room with a table and a box. Then, they play through a tutorial stage with three simple puzzles and a background image with instructions as seen in Figure 5.7. Participants learn how to use their hands to move blocks, stack blocks, and assemble structures. Each completed puzzle lowers into the ground and a new puzzle rises to take its place. Once the tutorial stage is completed, participants are asked to let the researchers know when they are ready for the main puzzles.

The main puzzles (see Figure 5.8) take place in the same box as the tutorial puzzles. After every two puzzles, the questionnaire appears in place of the puzzle instructions and participants read their answers aloud for the researcher to record. After the questionnaire, the next puzzle rises and the avatar switches to the next hand size condition.

Halfway through the main puzzles, participants are given a break as they switch from using one interaction modality to complete the remaining six puzzles with the other interaction modality. After completing all puzzles, participants are asked to remove the headset for a post-study interview. Replies are scribed for qualitative feedback.

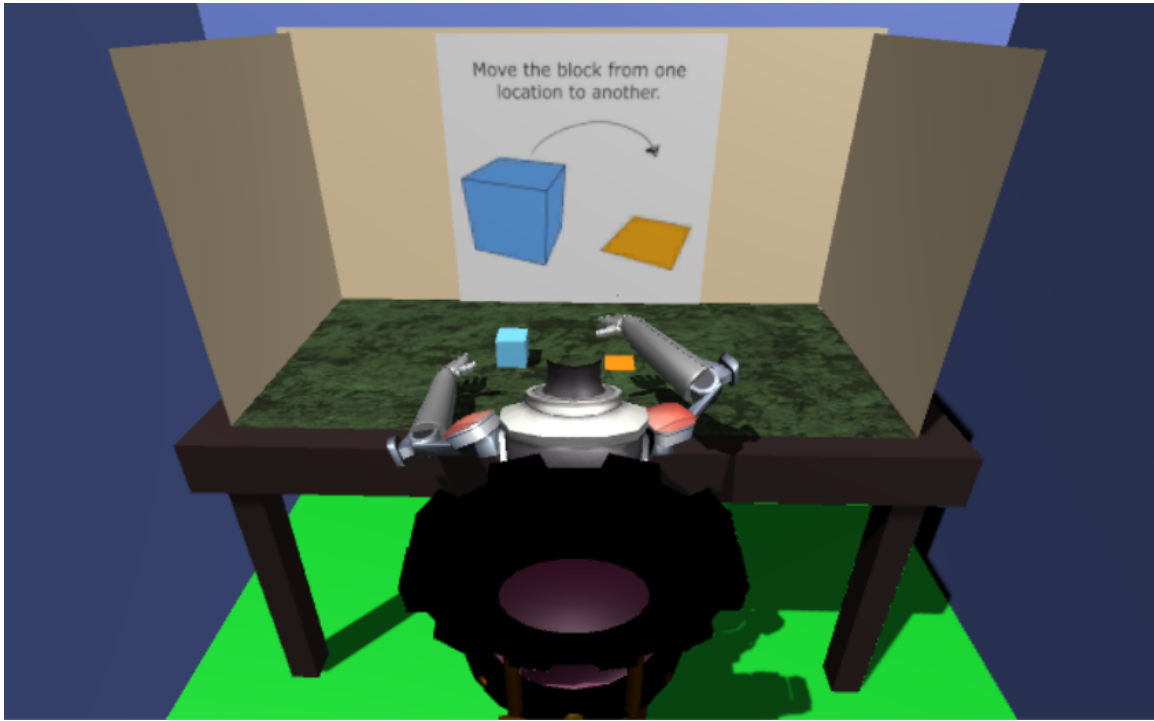


Figure 5.7: Avatar and environment in one of the tutorial puzzles.

5.2.5 Questionnaire

Table 5.1 shows our study questionnaire given after participants experience each condition by playing two puzzles. The full questionnaire can be found in Appendix L. The dependent variables are measured by asking participants to rate statements testing ownership and implications or signs of ownership. We furthermore ask questions about agency, realism, immersion, efficiency, and likability. Statements from the standard Botvinick and Cohen 9-question survey [13] altered for the virtual hand illusion by Ma and Hommel [49] [50] [51], Yuan and Steed [95], Zhang and Hommel [97], Argelaguet et al. [2], and Lin and Jörg [43] have been adapted for this experiment. For each statement, participants choose a rating on a seven-point Likert scale ranging from 1 for “strongly disagree” to 7 for “strongly agree.” The one exception from the Likert scale format is the last question on the list, in which participants report their virtual hand size from 0 to 200 percent of their real one. Statement order is randomized in the study.

5.3 Results

5.3.1 Questionnaire

We conducted the aligned rank transform procedure [90] followed by a 2x3 two-way repeated measures ANOVA on the questionnaire results with the modality (Glove vs. Controller) and hand size (Small vs. Fit vs. Large) as the within-subjects factors. Mauchly's test of sphericity was conducted. For questionnaire statements that did not pass Mauchly's test, we applied a Greenhouse-Geisser correction on the data. Main and interaction effects were found for several of our questionnaire items (see Table 5.1 for an overview as well as Figures 5.9, 5.10, and 5.11. Error bars represent the standard errors of the mean in all graphs.)

Ownership. We found an interaction effect for ownership statement **O1**. "I felt as if the virtual hands were part of my own body" with $F(2,38) = 3.8$ and $p = 0.031$. Pairwise comparisons with LSD corrections showed that ownership was rated higher in the Glove condition ($M = 4.8$, $SE = 0.452$) than in the Controller condition ($M = 3.7$, $SE = 0.357$) with the Small hands, whereas there was no difference between the conditions with the Fit or Large hands (see Figure 5.9 (a)). No effects were found for separately analyzing the ownership questions:

- **O2**. "It sometimes seemed my own hands were located on the screen."
- **O3**. "It sometimes seemed my own hands were coming into contact with the virtual objects."

When analyzing the three ownership statements together, we found a main effect of modality where the Glove condition generates a higher level of ownership than the Controller condition (see Figure 5.9 (b)). Cronbach's alpha for the three ownership statements was 0.943.

Agency. No effects were found for analyzing the agency statements separately and together:

- **A1**. "I felt as if I could cause movements of the virtual hands."
- **A2**. "It felt as if I could control movements of the virtual hands."
- **A3**. "I felt as if the virtual hands moved just like I wanted them to, as if they were obeying my own will."

Cronbach's alpha for the three agency statements was 0.938.

Realism Participants felt like the virtual hands looked more realistic in the Glove condition. Analysis of the realism statement Q1 revealed a main effect of modality where participants rated the Glove condition

higher than the Controller condition (see Figure 5.10 (a)). We also found a main effect of size, but pairwise comparisons did not reveal any significant difference.

Efficiency. We found a main effect of modality for the efficiency statement Q3. The Controller condition was perceived as more efficient than the Glove condition (see Figure 5.10 (b)).

Likability. Analysis of likability statement Q4 revealed a main effect of size. Participants liked the Fit hand more than the Large hand (see Figure 5.10 (c)).

Fun. We found a main effect of size, but pairwise comparisons did not reveal any significant difference between sizes.

Perceived size. For size statement Q6 we found a main effect of modality where participants rated hands in the Controller condition as larger than in the Glove condition (see Figure 5.10 (d)). Participants were able to differentiate between the hand models as shown by the main effect of size with all differences being significant. Participants overestimated the size of their hands in virtual reality.

5.3.2 Play Data

To give us further insights into participants' behavior, we analyzed the play duration, number of times blocks were grabbed, and number of times blocks were dropped using the same methods as for the questionnaire. The number of drops does not include successful block placements. Our analysis showed a main effect of duration in modality (see Figure 5.11 (a)). Participants spent more time in the Glove condition than in the Controller condition. An interaction effect showed that participants spent more time in the Glove condition with the Small and Large hands than in the Controller condition with the Small and Large hands. In addition, in the Controller condition, participants spent more time with the Fit hands than the Small or Large hands.

We found a main effect in modality where participants grabbed blocks more often in the Glove condition than in the Controller condition. There was also an interaction effect in the Controller condition where participants grabbed blocks more in the Fit than the Small condition. Finally, there was a main effect of modality where participants dropped blocks more in the Glove than in the Controller condition.

Participant move trajectories were recorded as well. Figure 5.12 illustrates the difference in movement between the Glove and Controller condition in a participant's trajectory visualization.

5.3.3 Qualitative Findings

We asked participants in our post-study interview if they experienced dizziness or disorientation during or after the study. We also debriefed them on the independent variables and asked if they had a preference for modality and hand size.

One participant felt “a little [disorientation]” while wearing the headset and another participant’s head physically hurt from wearing it, but all 20 participants reported that they did not experience dizziness or disorientation after taking off the headset.

Eight participants preferred the Fit hand size, citing reasons such as “they seemed to work best,” and “it felt more like it was part of my body.” Four participants preferred Fit or Small hands. One participant preferred the Small hands “for more precise movements.” Three participants preferred Large hands as they were “easier to manipulate the objects with,” and “the funnest.” Two participants preferred the Fit and Large hands, “the smaller one might be the one I had more trouble with,” “I didn’t like the small ones.” The Large hands were also reported as “unrealistic, it [looks] too big to me,” “most difficult [size] to work with,” and “it felt like a kid’s version of the game.” One participant said they preferred hand size based on the size of the block they were moving, preferring the Small hands for “better dexterity” and reporting the Large hands as “floppy” but preferred for more “macro applications (bigger blocks).” One participant reported not noticing the Small hands, saying they would prefer a smaller hand size if we had made one for the study.

Thirteen participants preferred the Glove condition, citing reasons such as the gloves were “easier to control,” “it felt more realistic,” “more immersive,” “more fun,” “more comfortable,” “I prefer the gloves since I was able to move all of my fingers and it looked just like my own hands,” and “with the gloves it felt much more physical, like I was building with my hands than versus the controllers,” and “I felt like I was [going to] drop the controllers because I had to keep thinking ‘I’m using controllers, I can’t let go of these.’” Four participants who preferred the Glove condition reported that they felt the Controller condition had better feedback. Six reported preferring the controllers because “it was more precise when I was picking things up,” “more responsive,” “the gloves were more immersive, but the controllers seemed to work better,” “with the gloves there wasn’t any real feedback.” One controller-preferring participant would prefer the gloves if they “worked like my real hands.” One participant had no preference for modality.

5.4 Discussion

We confirmed our hypothesis that being able to directly control virtual hands rather than use a controller induces a stronger level of virtual hand ownership and thus increases the virtual hand illusion. It is noteworthy that, in contrast to Argelaguet et al. [2], we did not find that agency is stronger for hands less similar to participants'. Although there were no differences for agency among our conditions, like Lin and Jörg [43], we found that participants generally had high ratings for feeling like they could control the hands. Being able to move the hands may have been enough to generate similar feelings of agency among our models. Since grasping was the only task and buttons were assigned to the controllers to mimic a grasp, our button implementation may have been convincing enough to place the controllers on a similar agency level with the gloves as well.

There were multiple main effects of modality showing differences in areas beyond ownership. Though we did not change the robot model throughout the study, participants thought the hands looked more realistic in the Glove condition, which could be attributed to the fact that they were able to move individual fingers in that condition, thus creating more natural-looking hand motions. Our play data supported participants' perceived efficiency for the Controller Condition over the Glove Condition. One reason for these findings might be in the tracking and grasp detection. While our motion capture system was well calibrated and our thresholds for grasp detection were carefully adjusted, grasp detection is still less reliable than a button press [40]. Users might also feel more in control when having haptic feedback in the form of a button.

In contrast to Wittkopf et al. [89]'s findings, we could not confirm our hypothesis that having a hand size similar to one's own induces a stronger virtual hand illusion. Like Ogawa et al. [63], we observed that participants overestimate virtual hand size. Participants also perceived hands as being larger in the Controller condition. They could have been able to judge the body part better in the Glove condition because they were directly controlling it [47]. Several participants were observed playing with the finger movements throughout the study in the Glove condition. Being able to look at and control individual finger movements could have made participants more self conscious, and thus better at judging their hand sizes.

Finally, we did not find any consistent differences due to interaction modality or hand size for some of our statements, most interestingly Q2 and Q5, which are related to immersion and fun. Our puzzles may have been entertaining enough to create a fun and immersive experience independent of the interaction or hand model. Different effects could also have balanced each other out. For example, a higher feeling of ownership could increase fun and immersion in the glove condition, whereas a less efficient control of the grasping might

reduce them.

5.5 Conclusion and Future Work

We found multiple main effects of modality, showing that being able to directly manipulate the environment with gloves increases feelings of ownership, accuracy in judging virtual hand size, and the perception of realism for the virtual model. Interestingly, participants preferred the Glove condition, despite the Controller condition resulting in better task performance.

Ownership, agency, realism, immersion, fun, and task efficiency were not directly affected by hand size in our study. However, the physical appearance of the virtual hands was preferred for the Fit hands over the Large hands.

In summary, the choice of the interaction modality should depend on the application: if realism and the intensity of the virtual hand illusion are important, we recommend using gloves; if task efficiency is the main focus, controllers should be used. An accurate hand size can be used to increase how much users like the appearance of their virtual hands. However, our results do not support any main effect of hand size on the virtual hand illusion or task efficiency. Finally, it seems that an interesting application might be fun and immerse players in any of the presented conditions.

Our experiment examines the effects of two interaction models and three hand sizes. There are several limitations of our setup which could be fruitful grounds for future work. For example, our interaction model does not integrate physics simulation. Specifically, blocks were allowed to intersect and did not react to gravity, so the movement of blocks is not consistent with the real world. Our study also focused on interacting with objects in a range of sizes likely to be handled in reality. A future study could observe if results for our conditions, especially hand sizes, differ when the same puzzles are scaled at smaller or larger sizes.

Furthermore, the avatar's shape and motion differs slightly from the participant's. The avatar hand shape and motion are both retargeted from a more faithful representation of the users hand. For example, the fingers of the avatar are aligned in a straight line across the palm with even spacing between them and the palm is rigid. A more realistic hand model could influence our observations.

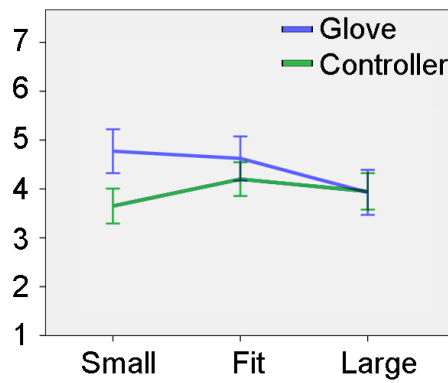
Finally, future work could investigate further ways to combine efficiency with realism. Haptic feedback could be added to gloves or grasp detection could be improved by examining user intent.



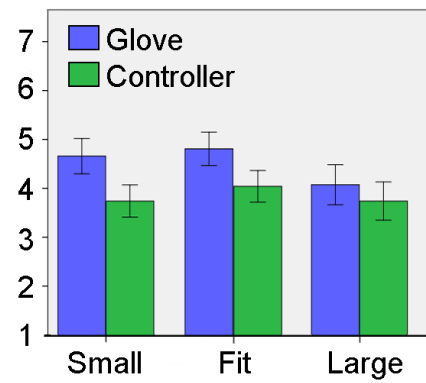
Figure 5.8: The 12 main puzzles in our study. The number of blocks ranges from 7 to 13 per puzzle.

Table 5.1: Questionnaire results for our study.

Questionnaire Item	Concept	F-test, p-value	Mean and Standard Error (M, SE)	Results
O. Three ownership statements averaged	Ownership	Main effect of Modality: $F(1, 19) = 7.22, p = 0.015$	Glove (4.5, 0.328) Controller (3.8, 0.326)	Controller < Glove
A. Three agency statements averaged	Agency		Overall average (5.3, 0.310)	
Q1. I thought the virtual hands on the screen looked realistic.	Realism	Main effect of Modality: $F(1, 19) = 8.01, p = 0.011$	Glove (4.0, 0.382) Controller (3.3, 0.362)	Controller < Glove
		Main effect of Size: $F(2, 38) = 3.83, p = 0.030$	Small (3.9, 0.404) Fit (3.7, 0.327) Large (3.3, 0.370)	
Q2. I was so immersed in the virtual reality, it seemed real.	Immersion		Overall average (4.6, 0.385)	
Q3. I felt like I could very efficiently use my virtual hands to interact with the environment.	Efficiency	Main effect of Modality: $F(1, 19) = 6.46, p = 0.020$	Glove (4.6, 0.320) Controller (5.2, 0.291)	Glove < Controller
Q4. I liked the physical appearance of my virtual hands.	Likability	Main effect of Size: $F(1.37, 26.1) = 5.61, p = 0.018$	Small (4.5, 0.334) Fit (4.6, 0.292) Large (3.9, 0.366)	Large < Fit
Q5. I felt like using my virtual hands to interact with the environment was fun.	Fun	Main effect of Size: $F(2, 38) = 3.38, p = 0.044$	Small (5.7, 0.333) Fit (5.9, 0.306) Large (5.5, 0.352)	
Q6. What size were your virtual hands?	Perceived size	Main effect of Modality: $F(1, 19) = 6.15, p = 0.023$	Glove (123, 6.5) Controller (135.4, 6.8)	Glove < Controller
		Main effect of Size: $F(1.27, 24.1) = 120.7, p < 0.001$	Small (89.8, 4.5) Fit (124.1, 5.0) Large (173.8, 11.1)	Small < Fit < Large
Duration	Play Data	Main effect of Modality: $F(1, 19) = 17.12, p < 0.001$	Glove (185.6, 10.5) Controller (144.2, 11.1)	Controller < Glove
		Interaction effect Size x Modality: $F(2, 38) = 7.09, p = 0.002$	Glove Small (206.1, 19.5) Glove Fit (173.6, 19.5) Glove Large (177.0, 12.0) Controller Small (137.4, 13.8) Controller Fit (178.5, 18.784) Controller Large (166.6, 7.9)	Controller Small, Controller Large < Glove Small, Glove Large; Controller Small, Controller Large < Controller Fit
Number of Grabs	Play Data	Main effect of Modality: $F(1, 19) = 56.71, p < 0.001$	Glove (67.9, 3.86) Controller (40.0, 1.69)	Controller < Glove
		Interaction effect Size x Modality: $F(2, 38) = 6.26, p = 0.004$	Glove Small (74.7, 6.55) Glove Fit (63.05, 5.6) Glove Large (66.1, 4.4) Controller Small (35.0, 2.4) Controller Fit (44.4, 2.8) Controller Large (40.7, 2.7)	Controller Small < Controller Fit
Number of Drops	Play Data	Main effect of Modality: $F(1, 19) = 8.93, p = 0.008$	Glove (24.7, 0.585) Controller (22.4, 0.375)	Controller < Glove

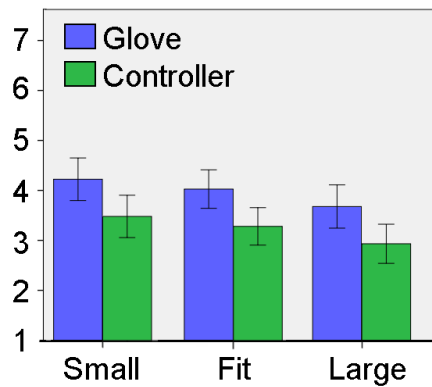


(a) Ownership O1
Interaction effect

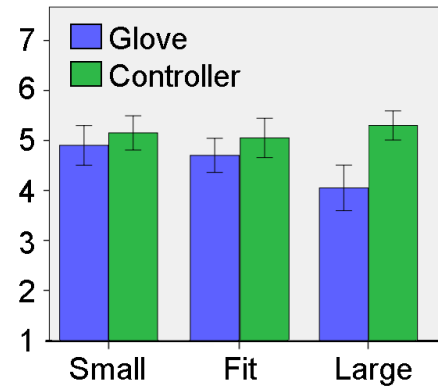


(b) Ownership O
Main effect of modality

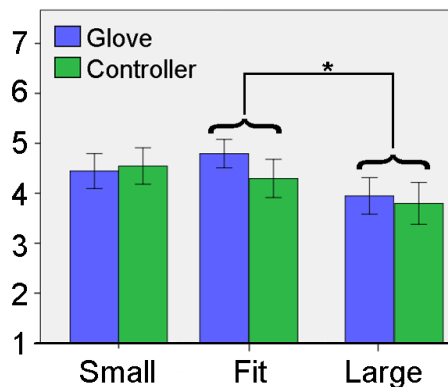
Figure 5.9: Significant results for ownership statement O1 and all ownership statements averaged.



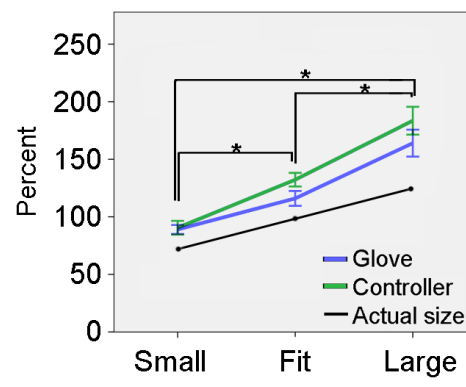
(a) Realism Q1
Main effect of modality
Main effect of size



(b) Efficiency Q3
Main effect of modality



(c) Likability Q4
Main effect of size



(d) Perceived size Q6
Main effect of modality
Main effect of size

Figure 5.10: Significant results for statements Q1-Q6.

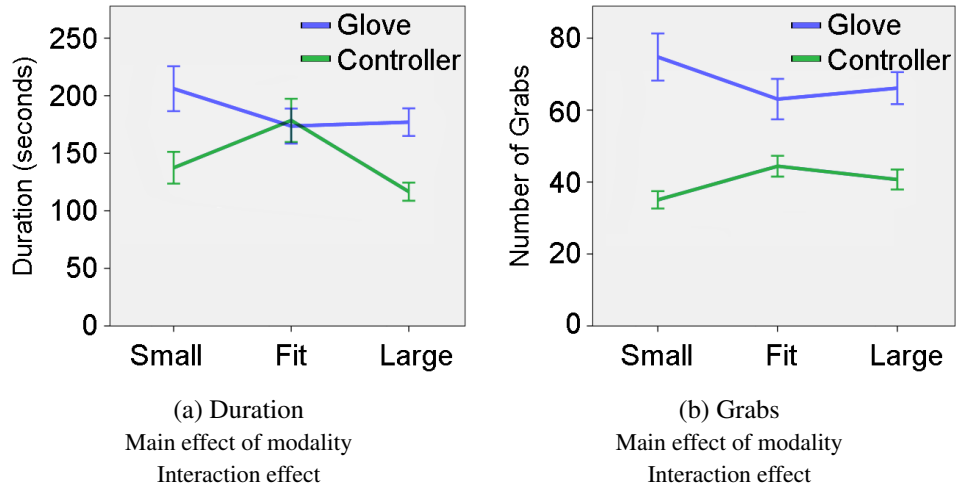


Figure 5.11: Significant results for the play data. The main effect of modality for Drops is not represented. The averages are for two puzzles as we had two puzzles in each condition.

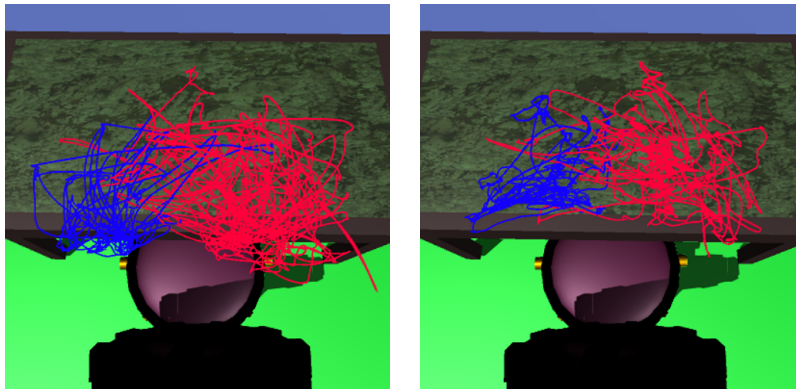


Figure 5.12: A participant's trajectory visualization in the Glove condition (left) and in the Controller condition (right). In both conditions, this participant used their right hand more than their left. They also moved their hands more in the Glove condition.

Chapter 6

Contributions

We conducted three studies on character appearance on ownership and learning in virtual applications, and we conclude that the appearance of virtual characters matters.

In our first study, we observed the effects of character customization on learning. My team and I asked middle school students to try out the existing teaching application VEnvI, or Virtual Environment Interactions. VEnvI is a two-to-three week curriculum that teaches computational thinking through dance. In each session, students learn a dance sequence, such as part of the Cha Cha Slide, then they learn a computing concept, and are asked to code their dance moves into the VEnvI interface. We found that, when we gave participants the option to customize characters, they had increased performance in being able to remember and understand new information.

In our second study, we observed the virtual hand illusion, which is the phenomena of participants taking on virtual hands as a part of themselves. Users controlled six different virtual hands: three human hands with differing levels of realism, a robot and zombie hand for differing levels of sensitivity to pain, and a control wooden block hand. Participants used their virtual hands to block spheres coming at them, and had a virtual knife sink into their virtual hand. Our findings indicate that an illusion can be created for any model for some participants, but that the effect is perceived weakest for the block model and strongest for the realistic human hand model in direct comparison. We furthermore found that the responses to our experiments highly vary between participants.

We observed how the virtual hand illusion is affected by changing the size of the virtual hand as well as interaction modality in our third study. Participants were asked to make virtual structures out of virtual toy blocks. They were able to try out a virtual hand that was the same size, smaller, or larger than their own hand

during the study. They were also able to interact with the environment with either oculus touch controllers or motion capture gloves. We found that participants prefer the appearance of hands that match their size over larger hands.

Our studies suggest that virtual application designers should consider the purpose of the application to determine the appearance of the character, offer customization for learning platforms, and offer realistic human hands for the highest feeling of ownership. Finally, applications should offer fitting hands over larger hands for users to like them the most. The results from our research contribute to knowledge on how to best create characters for virtual applications such as digital games, educational software, training simulations, or rehabilitation applications. This knowledge is important for optimizing learning applications, increasing user learning and motivation, and creating virtual environments in which we feel comfortable and in which we can effectively interact to learn, work, communicate, and have fun.

Appendices

Appendix A Study 1: VEnvI Teaching Plan

RESEARCH OVERVIEW

Evaluation Questions

- Is VENVI successful in teaching the students basic programming concepts?
- Does the software enhance their interest towards the field of computer science and other related STEM fields?
- Does virtual reality add to the novelty and excitement of learning programming through VENVI, and further enhance students' interest in computer science?
- Does the ability to customize their characters, or the appearance of the characters that the students program play a role in increasing interest and excitement of learning withing VEnvI?
- Do students feel a higher sense of presence, or the feeling of being there inside the virtual environment, when experiencing immersive virtual reality as compared to a non-immersive experience?
- Are the students more active and willing to dance with their programmed virtual characters in the immersive VR experience compared to the non-immersive experience?

Research Question

- How does the grounded embodied curriculum, immersive interaction using virtual reality, and virtual peer customization support the development of computational thinking?

IN-DEPTH OVERVIEW

Session 1

Location: RCE Classroom

People: Lorraine, Dhaval, Dr. Leonard

Time: 50 minute session

Activities: In general, session will be utilized for introductions, purpose of the program, introducing students to the programming environment, and learn basic dance steps.

XX:00 - XX:30 Introductions and Pre-surveys

- Introductions from the team, ask students what research means, explain why we are asking them to fill out questionnaires
- Demographics and cognition questionnaire

XX:30 - XX:40 Discussion

Discussion Questions

- What is VENVI?
 - VE to introduce computational programming using movement, primarily dance.
 - What is computational programming, why is it important?
 - How are dance and programming related?
 - Program and choreograph virtual character, opportunity to perform with it.
 - How was it created? Motion capture, games, programming.
 - You can make something like this. Programming can be fun.
- What are we doing over the weeks?
 - Learning dance concepts, learning programming concepts, learning VENVI, working on basic choreography concepts to create a virtual-physical (informal) performance, having a competition / dance-off.
- Why are students participating?
 - Collecting data in this process about what you all think.
 - VENVI is under development so we want you to break it, try to find cool, new ways to play with it, SAVE often, be open to the fact that things might not work, and PLEASE give us feedback on making it better. This is research and development, the frontlines of creating a new program.
- What do they hope to do during the program? What expectations do they have?

XX:40 - XX:50 Warm-up activities and introduction to dance

Students will learn some of the choreography available in VENVI. This will be focused on Cha-Cha slide.

1. Warm-up: Breathing, body warm-up, walk around the room, eventually basic sequences (step

touches, grapevines)

2. Cha-Cha slide

Further options:

3. Basic sequences: step touches, grapevines, variations
4. Leader/Follower (if needed)
5. Learn 2 Denzel-inspired sequences
 - a. *Don't stop til you get enough* (MJ)
 - b. *Move on up* (Curtis Mayfield)

XX:50

Dismissal

Session 2

Location: RCE Classroom

People: Lorraine, Dhaval, Dr. Babu

Time: 50 minute session

Activities: Session will be utilized for introducing following three basic computational concepts to the students: sequences, loops, and parallelization.

XX:00 - XX:10 Programming concepts: Introduction

- What are computer scientists? What do they think computer scientists look like? What do computer scientists do?
- What is programming? Why is it important? Examples of applications.

XX:10 - XX:20 Programming concepts: Sequences

- What are sequences?
 - A particular order in which things follow each other.
 - Do sequences occur in real life?
- How do sequences relate to dance?
 - In dance, we call creating the dance as choreographing: piecing together the movements that make up a dance phrase, like in the Cha-cha slide - 2 steps right, 2 steps left... that is a dance phrase together with other phrases, like the hops, right, left, stomps, and the cha-cha phrase to create a dance sequence.
- Physical activity to demonstrate sequences.
 - Divide into groups. Have each person perform one move. Each group member performs their moves in a sequential order.

XX:20 - XX:35 Introduction to VENVI and the Immersive Visualization metaphor

On big screen, demonstrate basic functionality:

- VENVI interface
- Drag and drop
- Locomotor vs. non-locomotor
- Duplicate
- Play
- Sequences
- Saving work

Students will be introduced to the immersive visualization (IV) metaphor within VENVI.

- A demo will be setup before the students arrive. The visuals seen in the head-mounted display will be mirrored on the large screen display.

- IV will be introduced as a new way to see their character perform. They can do this at any point during programming.
- The demo will be shown on the large screen, performed by one of the researchers.
- Why should you try it out? What to watch out for? Will it be harmful in any way?

XX:35 - XX:50 Programming in VENVI

- Program the Cha-Cha slide moves together with the students.
- Some students will configure their characters during this time, but we won't specifically talk about it except for answering questions
- Students will make their own programmed choreography in VENVI

XX:50 Dismissal

Session 3

Location: RCE Classroom

People: Lorraine, Dhaval, Dr. Joerg

Time: 50 minute session

Activities: Session will be utilized for introducing VENVI and learning how to program in VENVI.

Ask about previous session. Which concepts did you learn?

XX:00 - XX:10 Programming concepts: Loops

- What are loops?
 - Perform something over and over again, a sequence that is repeated a number of times.
 - Do loops occur in real life? Examples.
- How do loops relate to dance?
- Physical activity to demonstrate loops.
 - Put your arms up in a V. Now put your arms in what's called a Low V [demonstrate]. Now that's our sequence: high V, low V. On the count of three, I want everyone to do the sequence. 1, 2, 3... Ok. Now I'm going to say a number, and that's how many times I want you to do that sequence. 2, 3, 4. Now this time I say a number, I want you to do the sequence fast. Ok? 6. [If funny, call it the bird loop].
 - Create sequence among divided groups. Give each group a random number to repeat their sequence. If easy, have them perform loops faster.

XX:10 - XX:20 Programming concepts: Parallelization / Do-Together

- What is parallelization?
 - Doing two or more things at the same time.
 - Do you do things together in real life? Examples.
- How does parallelization relate to dance?
- Physical activity to demonstrate do-together.
 - Divide into groups. Each group comes up with two moves (one for upper body; 2nd for lower body). Perform each move separately as a group; then both moves together as a group.

XX:20 - XX:30 Programming concepts: Summary and recall

- Can you tell me the three programming concepts we learned today?
- What does sequence mean? Can you give an example?
- What does loop mean? Can you give an example?
- What does do-together mean? Can you give an example?
- Can you mix and match these? What do you think? Can you have two of these concepts at the same time? Can you have all three concepts at the same time?

XX:30 - XX:35 Introduction to VENVI and the Immersive Visualization metaphor

On big screen, demonstrate basic functionality:

- Loops
- Do-together

XX:35 - XX:50 Programming in VENVI

- Change the Cha-Cha slide to use loops.
- Students will make their own programmed parallelization in VENVI (Mention that the upper body motion must be added first.)

XX:50 Dismissal

Session 4

Location: RCE Classroom

People: Lorraine, Dhaval, Dr. Joerg

Time: 50 minute session

Activities: Session will be utilized for learning few more computational concepts: variables, conditionals, and functions. Students will practice these new concepts within VENVI.

Ask about previous session. Which concepts did you learn?

XX:00 - XX:10 Programming concepts: Variables

- What are variables?
 - Something that can change, does not stay the same.
 - In programming, used to store information that can change.
 - Do variables occur in real life?
- How do variables relate to dance?
- Physical activity to demonstrate variables.
 - Ask students to clap and stomp, clap and stomp, with the number of stomps as the variable. Tell them to stomp 4 times between claps, then 3, then 2... (If they are into it, sing “We will, we will, rock you”)

XX:10 - XX:20 Programming concepts: Conditionals

- What are conditionals?
 - Do something if a requirement is met.
 - Do sequences occur in real life? If it’s not raining, I’ll go outside and play. Else, I’ll watch TV.
- How do conditionals relate to dance?
 - Examples can be lead and follow in dance: Only move forwards, or twirl, etc., if the leader directs it.
 - Whip and Nae Nae: You only do the Nae Nae if you do the whip first.
- Physical activity to demonstrate conditionals.
 - Each student has a move to perform. When the instructor raises hand (true), students perform their move. When the instructor’s hand is down (false), all movements cease.
 - Elimination Game
 - True = perform move. False = touch floor and still. Last person to perform false gets eliminated from game. Last person is winner.

XX:20 - XX:30 Programming concepts: Functions

- What are functions?
 - Functions are a set of actions, which are grouped together to form a procedure or routine.

- Do functions occur in real life? Examples. Getting ready for school every day is a routine.
- How do functions relate to dance?
 - When we're listening to music and sometimes when we're choreographing a dance, we might have repeated bars or moves.
 - So what's your favorite song that has a part that is repeated throughout? This is called the refrain or chorus.
- Physical activity to demonstrate functions.
 - Divide into groups. Each person in group comes up with one move. Create a sequence. Name their sequence. Instructor calls on random groups to perform their sequence.

XX:30 - XX:50 Programming in VENVI and IV metaphor

- Students will try out the new concepts in VENVI (Ask students to make a function out of a part of the Cha-Cha slide)
- Ask students to suggest music they want to program to, and bring their headphones to the next session. Tell students that their final performance should be 1 minute, 2 minutes max for the song they choose.

XX:50 Dismissal

Session 5

Location: RCE Classroom

People: Lorraine, Dhaval, Dr. Joerg

Time: 50 minute session

Activities: Session will be utilized to practice using VEnvI and the immersive visualization metaphor.

Ask about previous session. Which concepts did you learn?

XX:00 - XX:30 VENVi programming and IV

- Students will spend rest of the session programming for the 1-2 minute dance challenge.
- Students can experience IV anytime while programming.

XX:30 - XX:50 VENVi post-experiment questionnaire

- Students will answer questions related to their experience, presence, usability, and satisfaction within VEnvI and the immersive metaphor.

XX:50 Dismissal

Session 6

Location: RCE Classroom

People: Lorraine, Dhaval, Dr. Babu

Time: 50 minute session

Activities: Session will be utilized for conducting post-tests.

XX:00 - XX:30 Post-experiment cognitive questionnaire

XX:30 - XX:40 Dance challenge (tell them they don't get to do this till they finish above stage)

XX:40 - XX:50 Debriefing and closing

- Students will be thanked for taking part in the study.
- Students will be asked if they have any questions or comments.

XX:50 Dismissal

Appendix B Study 1: VEnvI Pre-Study Experience and Demographics Questionnaire

VEnvI Pre-Survey

PARTICIPANT ID: _____

COMPUTERS:

1. Is there a computer at home that you are allowed to use by yourself?
☐ Yes ☐ No
2. Do you have your own computer?
☐ Yes ☐ No
3. Do you have restrictions on computer use?
☐ Yes ☐ No
4. If so, please explain the type of restrictions you have, like, for how long, or what activities on the computer are not allowed, etc.
5. On average, how many hours a week do you think you spend using a computer?
☐ 0 ☐ 1-2 ☐ 3-5 ☐ 6-9 ☐ 10+
6. List three things you like to do on the computer.
7. Do you play video games?
☐ Yes ☐ No
8. If so, on what system do you play? (Choose more than one if you do use more than one system.)
 - ☐ Desktop or laptop (PC, Mac, etc.)
 - ☐ Tablet (iPad, Android tablet, etc.)
 - ☐ Mobile phones
 - ☐ Xbox
 - ☐ Xbox 360
 - ☐ PlayStation 4 (PS4)
 - ☐ PlayStation 3 (PS3)
 - ☐ PlayStation Portable (PSP)
 - ☐ Other: _____

9. Which game do you like to play the most, and why?

10. Have you ever played the following dancing games?

☐ Dance Dance Revolution

☐ Dance Central

☐ Just Dance

☐ Other: _____

11. Have you ever done computer programming before?

☐ Yes

☐ No

12. If so, please tell us what kind of programming you have done, or what types of programs you have worked on.

13. Describe any summer camps or after school activities have you been a part of that involve programming.

14. Have you ever heard of Scratch, ALICE, or Looking Glass (programming languages with animated characters)?

☐ Yes, I have heard of them and have used them before

☐ Yes, I have heard of them but have not used them before

☐ No, I have not heard of them

15. Do you know what a computer programming language is?

☐ Yes

☐ No

16. In one or two sentences, tell us what you think a programming language is.

17. Do you see yourself as a computer programmer?

☐ Yes

☐ No

18. Why do you, or don't you see yourself as a computer programmer?

19. Do you feel like you are confident at programming?

Not at all									Very much
1	2	3	4	5	6	7	8	9	10

Why or why not? :

20. I believe that being able to make a computer program is an important skill.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

21. I want to learn more about programming.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

22. How likely are you to choose computing as a major in college?

- ☐ Extremely Likely
- ☐ Likely
- ☐ Neutral
- ☐ Unlikely
- ☐ Extremely Unlikely

23. What do you think computer scientists do?

DANCE:

1. Have you ever participated in a formal dance program or dance class?
☐ Yes ☐ No
2. Do you enjoy dancing at home alone or with friends?
☐ Yes ☐ No
3. Do you watch dance on TV, internet, in movies, or as live performances?
☐ Yes ☐ No
4. If so, what type(s) of dance do you watch?
5. How much time do you spend dancing in a week?
☐ 0 hours ☐ 1-2 hours ☐ 2-4 hours ☐ 5-7 hours ☐ 8+ hours
6. Do you see yourself as a dancer? Why or why not?

24. Do you feel like you are confident at dancing?

Not at all									Very much
1	2	3	4	5	6	7	8	9	10

Why or why not? :

7. Do you see yourself as artistic? Why or why not?
8. I want to learn more about dance.
☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree
9. I want to learn more about choreography.
☐ Strongly Agree

- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

GENERAL INFORMATION

1. When is your birthday?
____ / ____ / ____
(month) (date) (year)
2. How much do you like school?
 - ☐ A lot
 - ☐ It's okay
 - ☐ A little
 - ☐ Not too much
 - ☐ Not at all
3. If you wish, please explain your answer to the previous question.
4. What is your most favorite subject in school?
 - ☐ Mathematics
 - ☐ Language Arts
 - ☐ Science
 - ☐ Social Studies
 - ☐ Other: _____
5. What is it about this subject that makes it your favorite?
6. What is your least favorite subject in school?
 - ☐ Mathematics
 - ☐ Language Arts
 - ☐ Science
 - ☐ Social Studies
 - ☐ Other: _____

7. What is it about this subject that makes you dislike it?

8. What do you like to do after school during your free time? Do you have an after school activity, class, etc.?

9. What languages do you speak at home?

10. How do you identify your race or ethnicity?

- ☐ White
- ☐ African American
- ☐ Hispanic
- ☐ Native American
- ☐ Asian
- ☐ Pacific Islander
- ☐ Multiracial
- ☐ Other: _____

11. How do you identify your gender?

- ☐ Female
- ☐ Male
- ☐ Other: _____

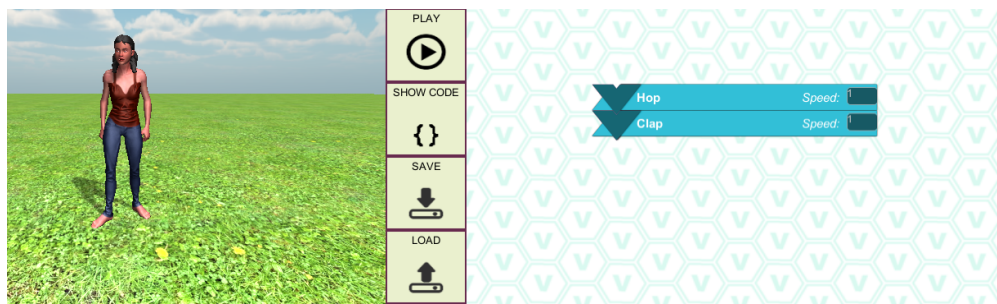
Appendix C Study 1: VEnvI Cognitive Questionnaire

VEnvI – Cognitive Questionnaire

PARTICIPANT ID: _____

COMPUTATIONAL THINKING

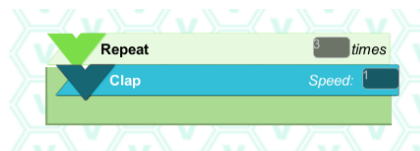
The picture below is from a software called VEnvI. The blocks on the right hand side tell the character how to dance. For example, when “PLAY” is pressed, the character will hop in the air and then clap her hands. The questions below will ask you about different ways the character can perform as well as your general understanding of computational thinking concepts. Please answer to the best of your ability.



1. The first block below (Picture A) will cause the character to clap twice. How many times will the character clap with the second set of blocks (Picture B)?



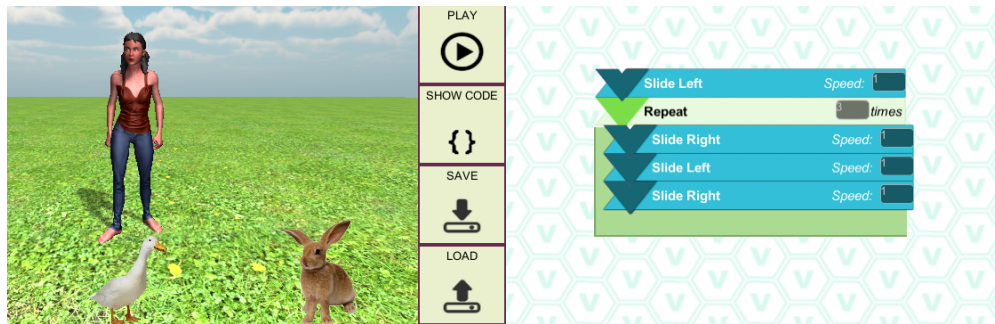
Picture A



Picture B

2. Based on the blocks below, if the character performs “Slide Left” she will be next to the rabbit. If she performs “Slide Right” she will be next to the duck. Once “PLAY” is clicked, when the character finished the moves in the code below, will she be next to the duck or the rabbit?

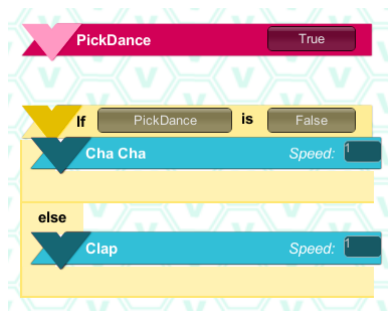
- ☐ Duck
- ☐ Rabbit



3. What is a variable? Explain in your own words. Give an example.

4. Based on the blocks below, will the character perform the “Cha Cha” or “Clap”?

- ☐ Cha Cha
- ☐ Clap

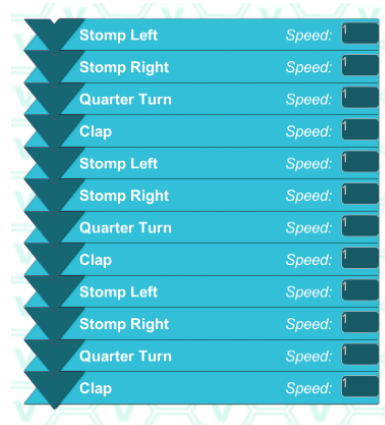


5. (a) Look at the blocks in Picture A and Picture B below. Would a character performing Picture A and another performing Picture B do the same thing?

- ☐ Yes
- ☐ No



Picture A



Picture B

(b) Look at the blocks in the pictures given in the previous question again. Which blocks (Picture A or Picture B) do you think are better to use? Why?

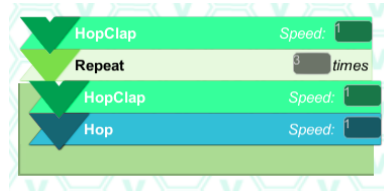
6. What is the purpose of a loop?

7. What is the purpose of a function?

8. The block in Picture A instructs the character to hop once while clapping. Based on the blocks in Picture B, how many times will the character hop?



Picture A

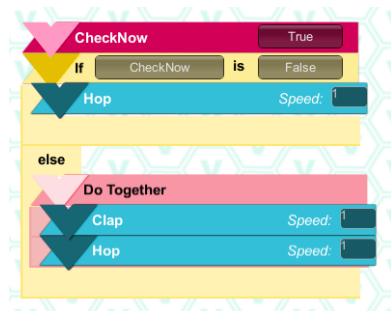


Picture B

9. What is a conditional statement in programming?

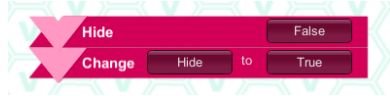
10. Give an example of a conditional in your life.

11. Look at the blocks below. When "PLAY" is clicked, what will the character perform?



12. What is the value of "Hide"?

- ☐ False
- ☐ True



13. What order should the blocks below be put into if I want the character to clap first, move to the right side, and then reverse twice?



14. Describe the steps you would use to make and eat a peanut butter and jelly sandwich.

Appendix D Study 1: VEnvI Post-Study Experience Questionnaire

VEnvI Post-Survey

PARTICIPANT ID: _____

1. Do you see yourself as a dancer? And/or a choreographer? Why or why not?

2. Do you feel like you are confident at dancing?

Not at all										Very much
1	2	3	4	5	6	7	8	9	10	

Why or why not? :

3. Do you see yourself as artistic? Why or why not?

4. I want to learn more about dance.

- ☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

5. I want to learn more about choreography.

- ☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

6. Do you know what a computer programming language is?

- ☐ Yes ☐ No

7. In one or two sentences, tell us what you think a programming language is.

8. Do you see yourself as a computer programmer?

☐ Yes ☐ No

9. Why do you, or don't you see yourself as a computer programmer?

10. Do you feel like you are confident at programming?

Not at all									Very much
1	2	3	4	5	6	7	8	9	10

Why or why not? :

11. I believe that being able to make a computer program is an important skill.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

12. I want to learn more about programming.

- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

13. How likely are you to choose computing as a major in college?

- ☐ Extremely Likely
- ☐ Likely
- ☐ Neutral
- ☐ Unlikely
- ☐ Extremely Unlikely

14. If not, what major do you think you will choose?

15. What do you think computer scientists do?

16. How likely would you participate in VEnvl again?

- ☐ Extremely Likely
- ☐ Likely
- ☐ Neutral
- ☐ Unlikely
- ☐ Extremely Unlikely

17. Please explain why or why not you would participate in VEnvl again.

Appendix E Study 1: VEnvI Debriefing and Character Questionnaire

Participant ID:

VEnvI Debriefing Questionnaire

About your experience:

1. How intense was your experience using VEnvI?

Not Intense					Very Intense				
1	2	3	4	5	6	7	8	9	10

Why? :

2. Did you feel like the experience within VEnvI involved you?

Not Involving					Very Involving				
1	2	3	4	5	6	7	8	9	10

Why? :

3. Did you feel like the environment in which the character was dancing was real?

Not Real					Very Real				
1	2	3	4	5	6	7	8	9	10

Why? :

4. Did you feel like you were inside the environment you saw?

Not Inside					I Was There				
1	2	3	4	5	6	7	8	9	10

Why? :

Participant ID:

5. Did you feel like you were immersed and surrounded by the environment you saw?

Not immersed					Completely Immersed				
1	2	3	4	5	6	7	8	9	10

Why? :

6. Did the presence of others around you affect your decision to dance or not?

Not at all					Very much				
1	2	3	4	5	6	7	8	9	10

Why? :

7. Did the presence of others around you affect your programming in VEnvI?

Not at all					Very much				
1	2	3	4	5	6	7	8	9	10

Why? :

8. Did the presence of the virtual character affect your decision to dance or not?

Not at all					Very much				
1	2	3	4	5	6	7	8	9	10

Why? :

9. Did the presence of the virtual character affect your programming in VEnvI?

Not at all					Very much				
1	2	3	4	5	6	7	8	9	10

Why? :

About your virtual character:

Participant ID:

10. How well do you like your character?

Not at all										Very much
1	2	3	4	5	6	7	8	9	10	

What do you like about your character? :

What do you dislike about your character? :

11. To what extent did you feel like you were in the same space/room as your character?

Not In The Same Room										We Were In The Same Room
1	2	3	4	5	6	7	8	9	10	

Why? :

12. How much did you feel like you were dancing as the character?

Not At All										Very Much
1	2	3	4	5	6	7	8	9	10	

Why? :

13. How interesting or engaging was your experience watching the character perform?

Not Interesting										Very Interesting
1	2	3	4	5	6	7	8	9	10	

Why? :

Participant ID:

14. Did you feel like the character was a partner you were dancing with?

Not At All										Very Much
1	2	3	4	5	6	7	8	9	10	

Why? :

15. Did you feel like the character was yourself?

Not At All										Very Much
1	2	3	4	5	6	7	8	9	10	

Why? :

16. Did you give the character a personality? If so, describe it.

17. To what extent did your character seem real?

Not Real										Very Real
1	2	3	4	5	6	7	8	9	10	

Why? :

Participant ID:

18. How much did you feel like dancing with the character?

Did Not Want To Dance											I Danced A Lot
1	2	3	4	5	6	7	8	9			10

Why? :

19. Did you create this character to be:

- ☐ Yourself
- ☐ A better version of yourself
- ☐ A friend
- ☐ A teacher
- ☐ Other: _____

About VEnvI:

1. Did you think it was easy to learn and use VEnvI? Explain.

Participant ID:

2. Would you use VEnvl a lot? How do you think you will use it? By yourself? With friends?
3. Do you think watching the character perform in this way will help you learn better? Give examples to explain.
4. What would make the virtual character more interesting for you?
5. What did you like/not like about VEnvl? Why?
6. How can you improve VEnvl? What would you like to change?
7. If you had more time to work on your project, what would you do next?
8. If you could make any type of project in VEnvl, what type of project would you make and why?

Thank you so much for taking the time to fill out this survey. Do you have any questions for us, or anything you wish we should have asked?

Appendix F Study 2: Demographics Survey

Preliminary Questions

1. Are you: male female
 ☐ ☐

2. How old are you?

18 – 21	21 – 25	26 – 30	31 – 40	41 – 50	51 – 60	over 60
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

3. Area of study/work: _____

4. How experienced would you rate yourself with virtual reality?

not at all							very experienced
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7	

5. How experienced would you rate yourself with virtual characters?

not at all							very experienced
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7	

6. How experienced would you rate yourself with video games?

not at all							very experienced
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7	

7. How left or right handed are you?

left-handed		ambidextrous				right-handed
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Appendix G Study 2: Experiment 1 VHI Questionnaire

For each statement, please select a number from 0 (strongly disagree) to 7 (strongly agree).

Q1. Sometimes I had the feeling that I was holding a real ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. I had the sensation that I felt the knife on my hand in the same location where the virtual hand on the screen was in contact with the knife.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. I felt like the sensation I felt on my hand was caused by the contact of the knife with the virtual hand on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. The movements of the virtual hand on the screen were caused by myself.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the knife that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. Sometimes I felt as if my real hand was becoming virtual.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. It seemed as if I might have more than one right hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q10. I anticipated feeling pain from the knife on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q11. During the experiment there were moments in which it seemed that my own hand was being hit by the knife.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q12. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

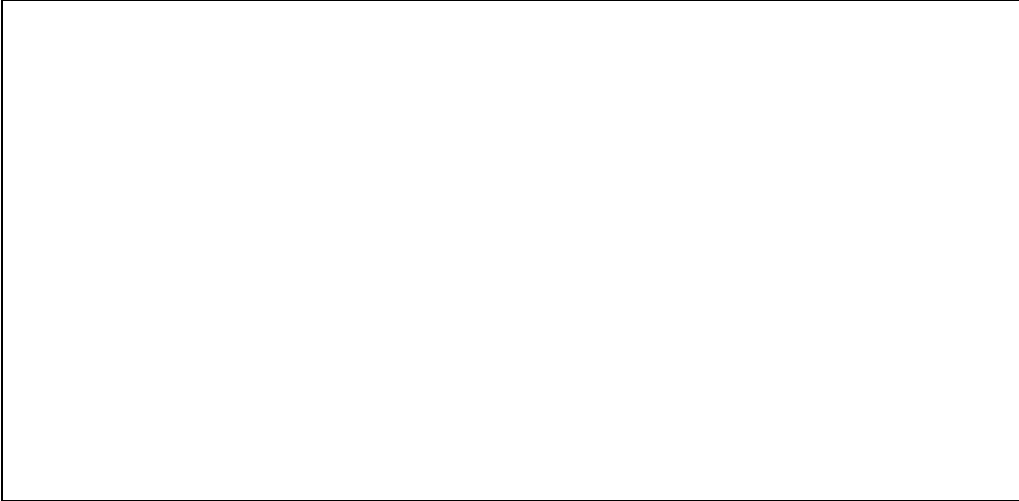
Q13. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Please write any comments you have here:

A large, empty rectangular box with a thin black border, intended for participants to write their comments.

Thank you for your participation!

Appendix H Study 2: Experiment 1 VHI Block Model Questionnaire

For each statement, please select a number from 0 (strongly disagree) to 7 (strongly agree).

Q1. Sometimes I had the feeling that I was holding a real ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. I had the sensation that I felt the knife on my hand in the same location where the virtual block on the screen was in contact with the knife.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. I felt like the sensation I felt on my hand was caused by the contact of the knife with the virtual block on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. The movements of the virtual block on the screen were caused by myself.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. The virtual block on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the knife that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. Sometimes I felt as if the virtual block on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. Sometimes I felt as if my real hand was becoming virtual.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. It seemed as if I might have more than one right hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q10. I anticipated feeling pain from the knife on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q11. During the experiment there were moments in which it seemed that my own hand was being hit by the knife.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q12. I thought the virtual block on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

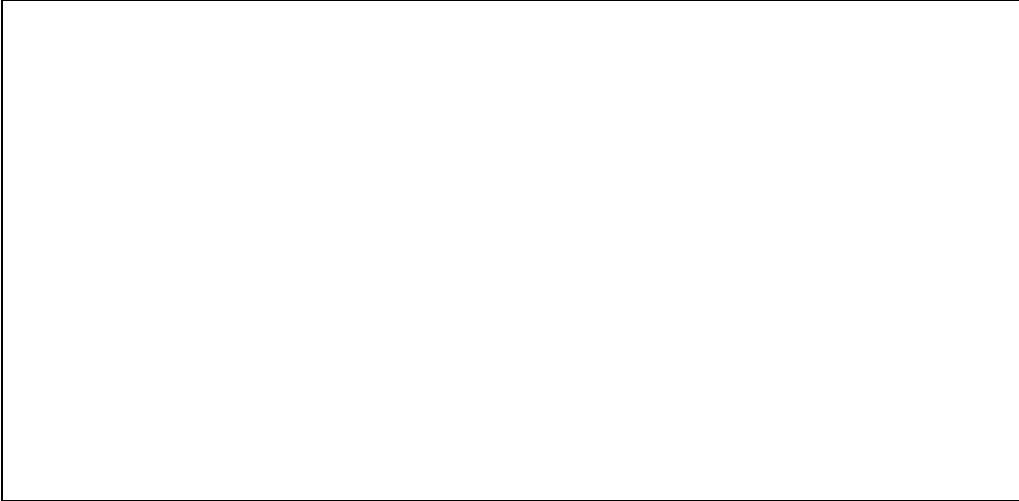
Q13. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Please write any comments you have here:

A large, empty rectangular box with a thin black border, intended for participants to write their comments.

Thank you for your participation!

Appendix I Study 2: Experiment 2 RHI Questionnaire

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand touched.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. It seemed as though the touch I felt was caused by the paintbrush touching the rubber hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. I felt as if the rubber hand were my hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. The rubber hand began to resemble my own (real) hand, in terms of shape, skin tone, freckles, or some other visual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Appendix J Study 2: Experiment 2 VHI Questionnaire

[For researcher use only. Instructions for Model 1]

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. The movements of the virtual hand on the screen were caused by myself.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. During the experiment there were moments in which it seemed that my own hand was catching the ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

[For researcher use only. Instructions for Model 2]

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. The movements of the virtual hand on the screen were caused by myself.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. During the experiment there were moments in which it seemed that my own hand was catching the ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

[For researcher use only. Instructions for Model 3]

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. The movements of the virtual hand on the screen were caused by myself.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. During the experiment there were moments in which it seemed that my own hand was catching the ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
--------------------------	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

1 2 3 4 5 6 7

[For researcher use only. Instructions for Model 4]

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q2. The movements of the virtual hand on the screen were caused by myself.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q3. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q4. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q5. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. During the experiment there were moments in which it seemed that my own hand was catching the ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

[For researcher use only. Instructions for Model 5]

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.

strongly disagree						strongly agree
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. The movements of the virtual hand on the screen were caused by myself.

strongly disagree						strongly agree
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. It sometimes seemed my own hand was located on the screen.

strongly disagree						strongly agree
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree						strongly agree
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q6. Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q7. During the experiment there were moments in which it seemed that my own hand was catching the ball.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q8. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q9. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

[For researcher use only. Instructions for Model 6]

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

Q1. I had the sensation that I felt the ball touch my hand in the same location where the virtual hand on the screen was in contact with it.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q2. The movements of the virtual hand on the screen were caused by myself.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q3. It sometimes seemed my own hand was located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q4. The virtual hand on the screen began to resemble my own hand in terms of shape, skin tone, freckles, or some other usual feature.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
--------------------------	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------	--------------------------

1 2 3 4 5 6 7

Q5. Sometimes I felt as if the virtual hand on the screen was my own hand.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q6. Sometimes it seemed as if what I was feeling was caused by the ball that I was seeing on the screen.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q7. During the experiment there were moments in which it seemed that my own hand was catching the ball.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q8. I thought the virtual hand on the screen looked realistic.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q9. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

[For researcher use only. Questions about the threat and overall study]

Q1. I had the sensation that I felt the knife on my hand in the same location where the virtual hand on the screen was in contact with the knife.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q2. I felt like the sensation I felt on my hand was caused by the contact of the knife with the virtual hand on the screen.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q3. Sometimes it seemed as if what I was feeling was caused by the knife that I was seeing on the screen.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q4. I anticipated feeling pain from the knife on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q5. During the experiment there were moments in which it seemed that my own hand was being hit by the knife.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Appendix K Study 3: Demographics Survey

Preliminary Questions

1. Are you: male female
 ☐ ☐

2. How old are you?

18 – 21	21 – 25	26 – 30	31 – 40	41 – 50	51 – 60	over 60
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

3. Area of study/work: _____

4. How experienced would you rate yourself with virtual reality?

not at all							very experienced
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7	

5. How experienced would you rate yourself with virtual characters?

not at all							very experienced
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7	

6. How experienced would you rate yourself with video games?

not at all							very experienced
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7	

7. How left or right handed are you?

left-handed							ambidextrous					right-handed
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
1	2	3	4	5	6	7						

Appendix L Study 3: Study Questionnaire

For each statement, please select a number from 1 (strongly disagree) to 7 (strongly agree).

O1: I felt as if the virtual hands were part of my body.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

O2: It sometimes seemed my own hands were located on the screen.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

O3: It sometimes seemed like my own hands were coming into contact with the virtual objects.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

A1: I felt as if I could cause movements of the virtual hands.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

A2: I felt as if I could control movements of the virtual hands.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

A3: I felt as if the virtual hands moved just like I wanted them to, as if they were obeying my will.

strongly disagree

strongly agree

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5	6	7

Q1. I thought the virtual hands on the screen looked realistic.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q2. I was so immersed in the virtual reality, it seemed real.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q3. I felt like I could very efficiently use my virtual hands to interact with the environment.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q4. I liked the physical appearance of my virtual hands.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q5. I felt like using my virtual hands to interact with the environment was fun.

strongly disagree

strongly agree

☐ ☐ ☐ ☐ ☐ ☐ ☐

1 2 3 4 5 6 7

Q6. What size were your virtual hands? (Please mark a point on the line.)

0% the size of

100% the size of

200% the size of

my real hands

my real hands

my real hands

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